Colloquium, Penn State University, March 20, 2014

Metamaterials and Metasurfaces: Principle, Structure, Functionality, and Application

Hou-Tong Chen

Center for Integrated Nanotechnologies (CINT)
MPA-CINT, MS K771, Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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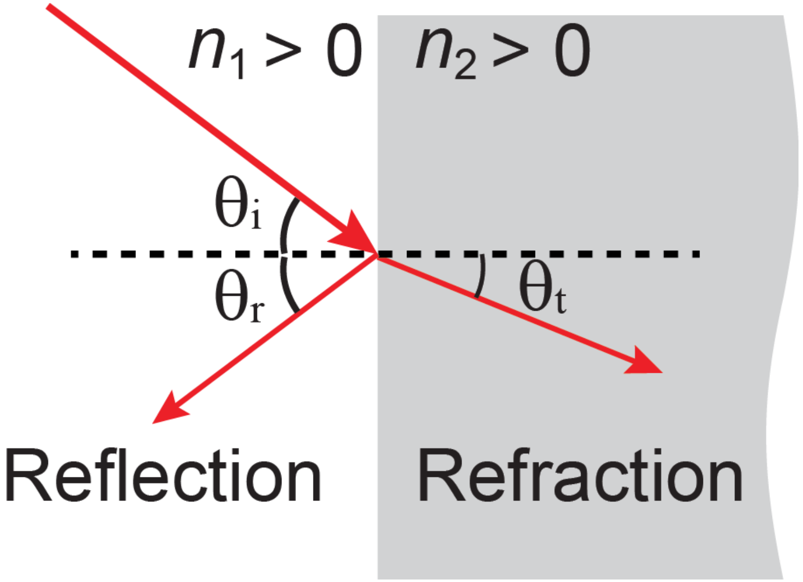
EST. 1943

Outline

- ☐ **Background introduction electromagnetic wave propagation**
- ☐ **Metamaterials and metasurfaces**
- ☐ **Few-layered metamaterials for**
  - ➢ **Antireflection coatings**
  - ➢ **Perfect absorption**
  - ➢ **Polarization conversion**
  - ➢ **Arbitrary wavefront shaping**
- ☐ **Summary**

Reflection and Refraction


$n_1 > 0$
$n_2 > 0$
θ_i
θ_r
θ_t
Reflection
Refraction

- ☐ Snell's law:

$$\theta_i = \theta_r$$

$$n_1 \sin\theta_i = n_2 \sin\theta_t$$

- ☐ Reflection & transmission coefficients: Fresnel equations
- ☐ Normal incidence ($\theta_i = 0$):

$$r = \frac{n_2 - n_1}{n_2 + n_1} \qquad t = \frac{2n_1}{n_2 + n_1}$$

Negative Index of Refraction

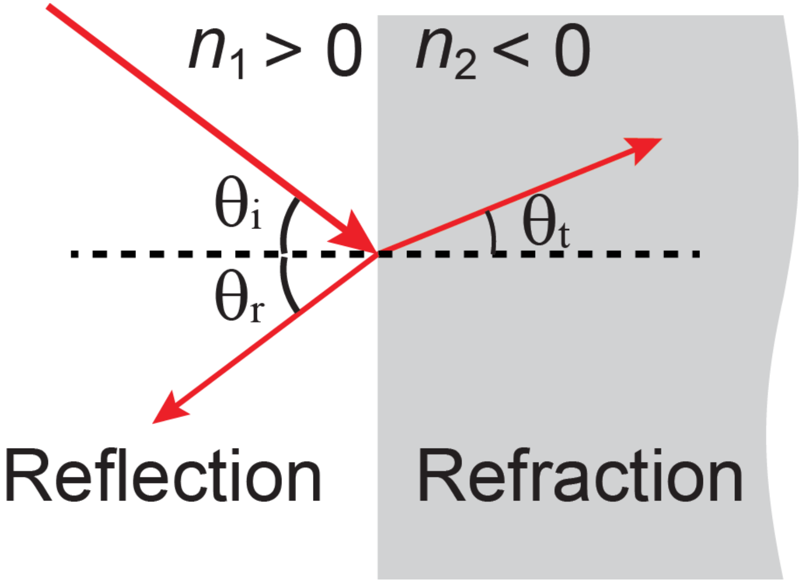
- ☐ Snell's law:

$$\theta_i = \theta_r$$

$$n_1 \sin\theta_i = n_2 \sin\theta_t$$

- ☐ Consequence:

$$\theta_t = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_i\right) < 0$$


$n_1 > 0$
$n_2 < 0$
θi
θr
θt
Reflection
Refraction

Refraction beam is at the "wrong" side of the surface normal

Permittivity, Permeability, Refractive Index …

- ☐ Electromagnetic wave equations:

$$\left(\nabla^2 - \frac{\varepsilon\mu}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{E} = 0 \qquad \left(\nabla^2 - \frac{\varepsilon\mu}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{B} = 0$$

ε: relative permittivity representing electric response

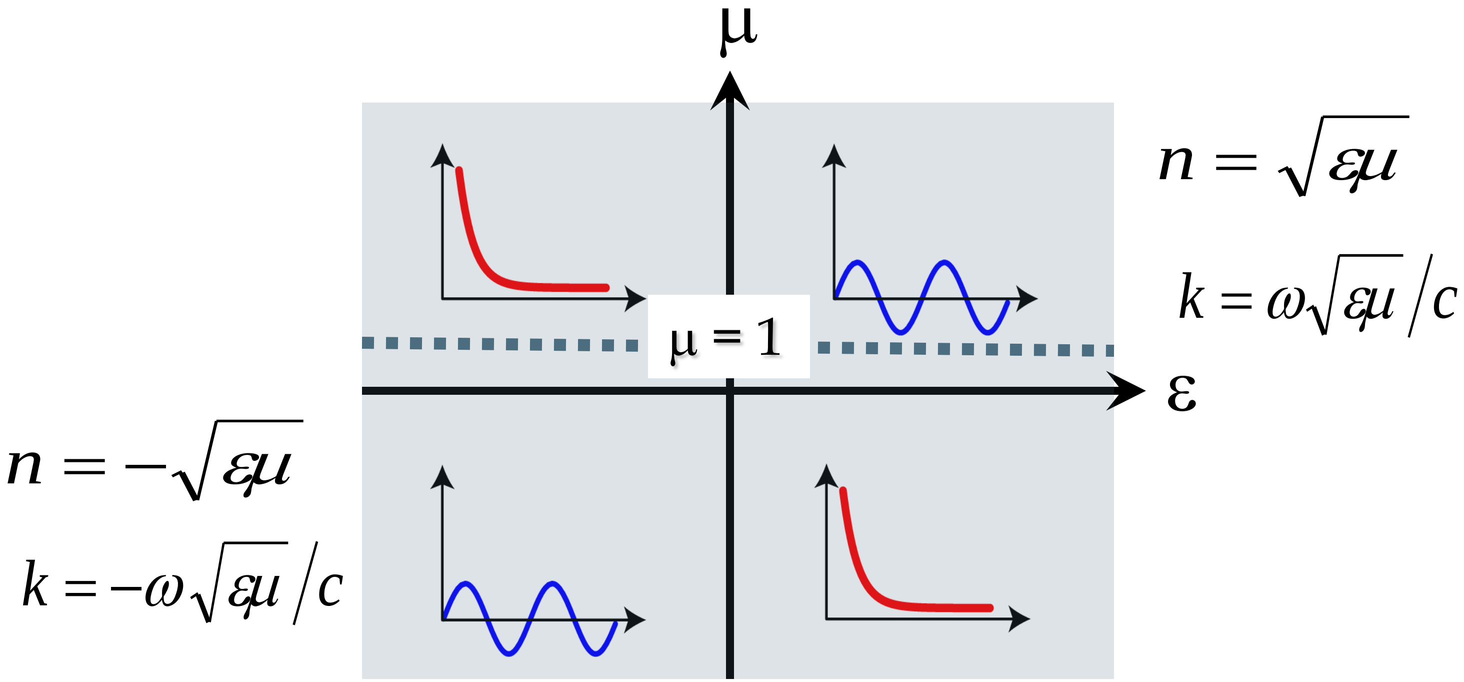
μ: relative permeability representing magnetic response

c: light speed in vacuum

Refractive index: $n^2 = \varepsilon\mu$

Wave vector (number): $k^2 = \dfrac{\omega^2}{c^2}\varepsilon\mu$

The ε-μ Diagram of Materials


μ
ε
μ = 1
$n=\sqrt{\varepsilon\mu}$
$k=\omega\sqrt{\varepsilon\mu}/c$
$n=-\sqrt{\varepsilon\mu}$
$k=-\omega\sqrt{\varepsilon\mu}/c$

- ❑ $\underline{\varepsilon > 0,\ \mu > 0:} \Rightarrow \varepsilon\mu > 0,\ n^2, k^2 > 0$ *propagating* waves
- ❑ $\underline{\varepsilon < 0,\ \mu > 0:} \Rightarrow \varepsilon\mu < 0,\ n^2, k^2 < 0$
  $\underline{\varepsilon > 0,\ \mu < 0:} \Rightarrow \varepsilon\mu < 0,\ n^2, k^2 < 0$ *evanescent* waves
- ❑ $\underline{\varepsilon < 0,\ \mu < 0:} \Rightarrow \varepsilon\mu > 0,\ n^2, k^2 > 0$ *propagating* waves

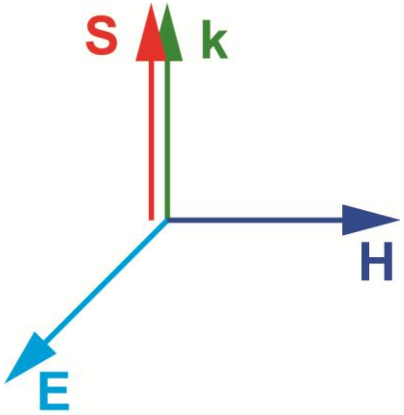
Left-Handed Materials

$$\mathbf{k}\times\mathbf{E}=\omega\mu\mathbf{H}$$

$$\mathbf{k}\times\mathbf{H}=-\omega\varepsilon\mathbf{E}$$

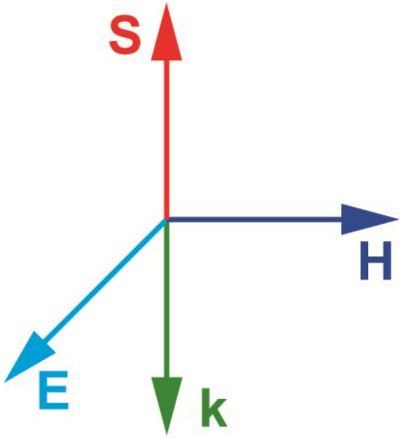
$$\mathbf{S}=\mathbf{E}\times\mathbf{H}$$

$\varepsilon>0, \mu>0$: **E**, **H**, **k** *right* handed



- $\mathbf{S}\uparrow\uparrow\mathbf{k}$
- $\mathbf{v}_{\text{group}}\uparrow\uparrow\mathbf{v}_{\text{phase}}$

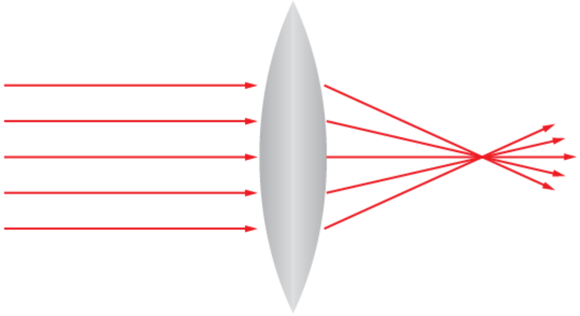
$\varepsilon<0, \mu<0$: **E**, **H**, **k** *left* handed



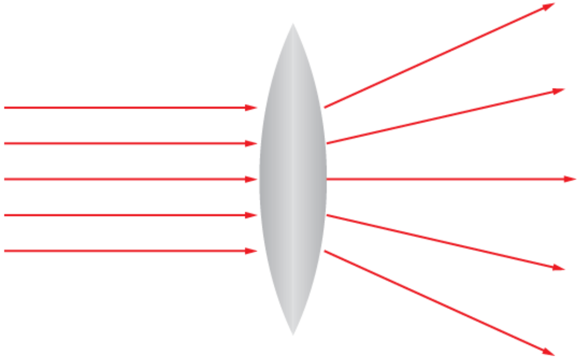
- $\mathbf{S}\uparrow\downarrow\mathbf{k}$
- $\mathbf{v}_{\text{group}}\uparrow\downarrow\mathbf{v}_{\text{phase}}$

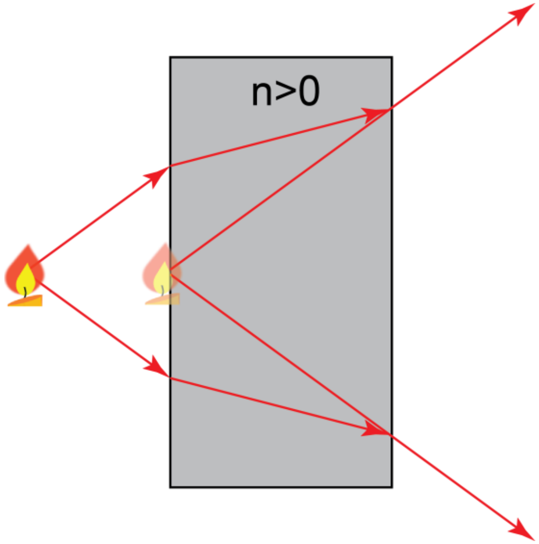
Lenses by Negative Refractive Index

positive index lens



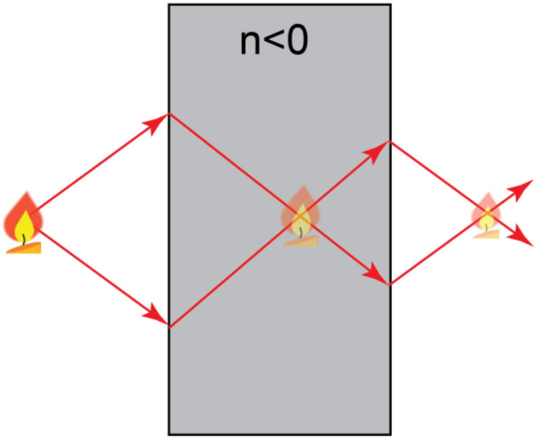
negative index lens





⇓

Diverging



⇓

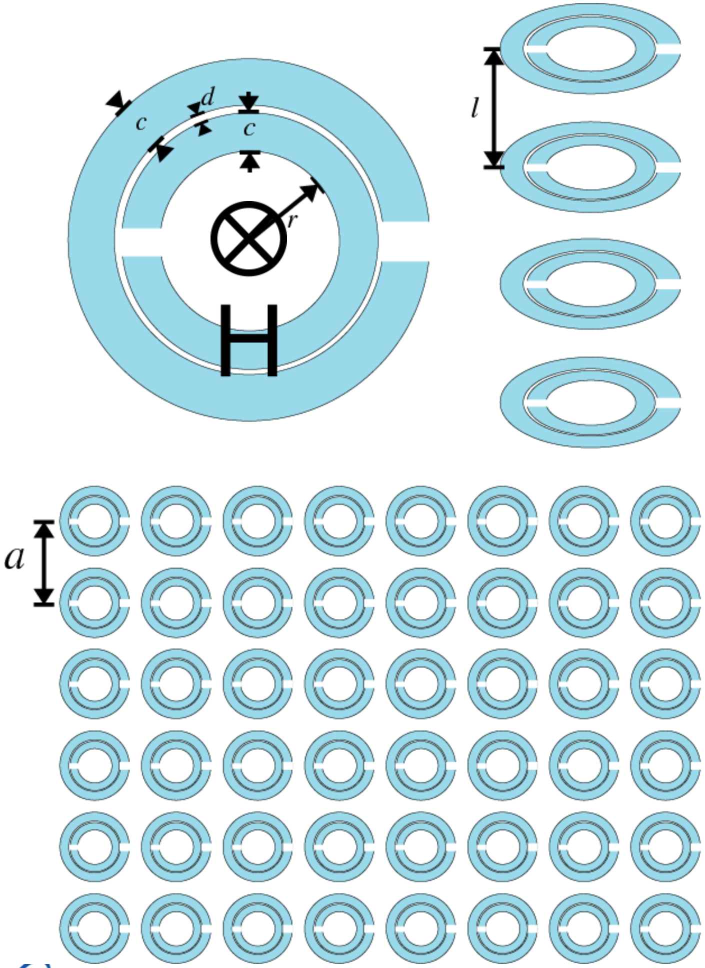
Focusing

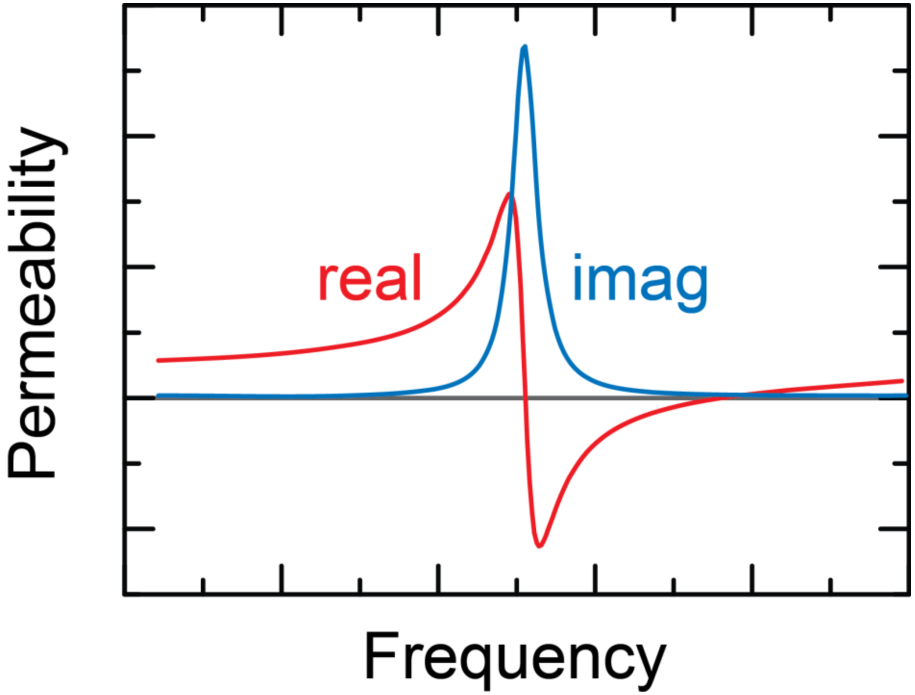
“Veselago Lens”

V. G. Veselago, *Sov. Phys. USP.* **10,** 509 (1968).

Negative Permeability

Magnetic resonance





Near the resonance frequency, the permeability can be negative

J.B. Pendry *et al.*, *IEEE Trans. Microwave Theory Tech.* **47**, 2075 (1999).

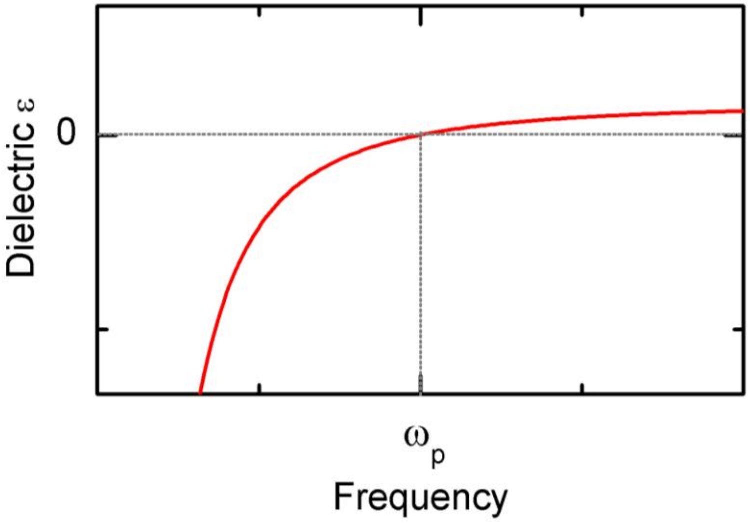
Negative Permittivity $\varepsilon_1 < 0$

Plasma (metal): Drude model

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 - i\omega\Gamma} \qquad \omega_p^2 = \frac{ne^2}{\varepsilon_0 m_e}$$

$\varepsilon_1 < 0$ when $\omega < \omega_p$

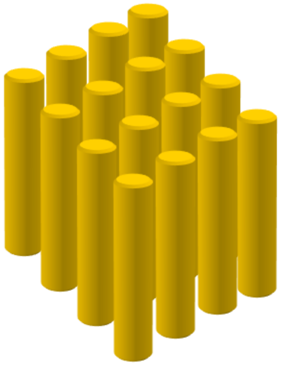
ω_p: UV or visible, *too high!*



Diluted plasma: lower ω_p

$$n\downarrow, m_e\uparrow, \omega_p\downarrow$$

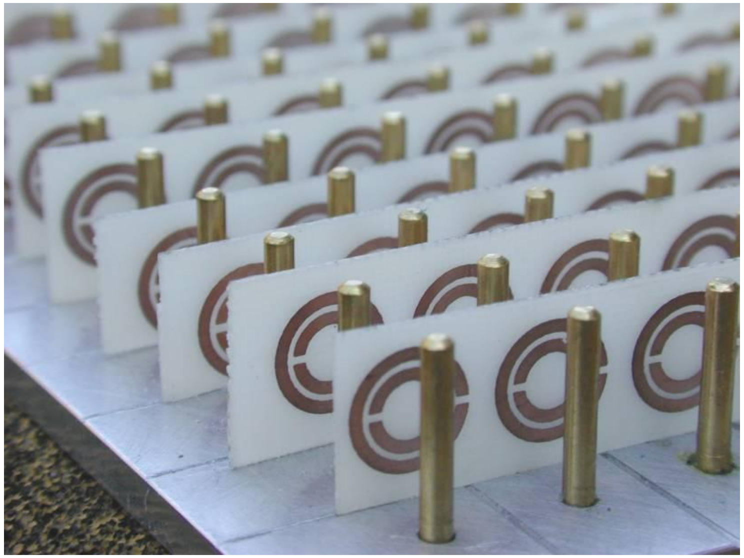
ω_p: THz or GHz



Metallic wires

J.B. Pendry *et al.*, *Phys. Rev. Lett.* **76**, 4773 (1996).

Electromagnetic Metamaterials

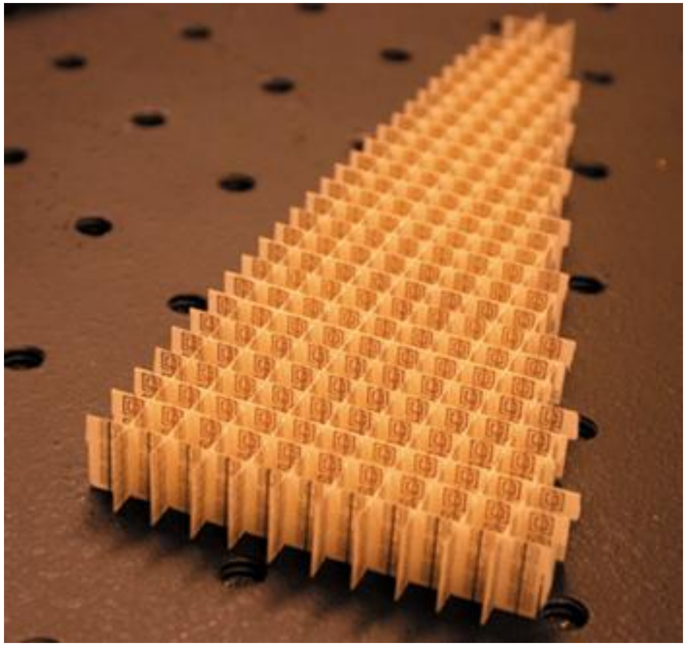


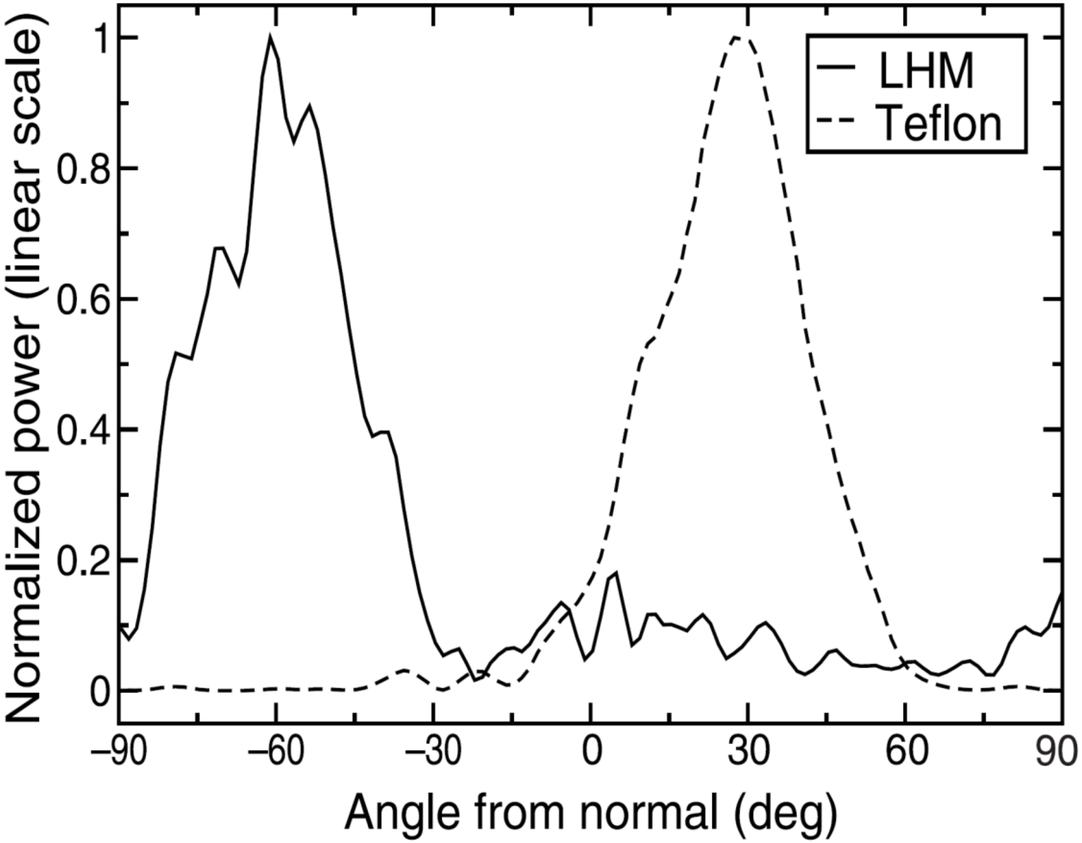
Composite metamaterials:
Negative permittivity and negative permeability
⇒ negative refractive index

Metamaterials are composed of sub-wavelength metal/dielectric structures (i.e. meta-atoms), which repeat in a periodic fashion mimicking two or three dimensional crystalline functional materials with exotic properties not normally found in nature.

D. R. Smith *et al.*, *Phys. Rev. Lett.* **14**, 234 (2000).

Negative Refraction: Prism Experiment

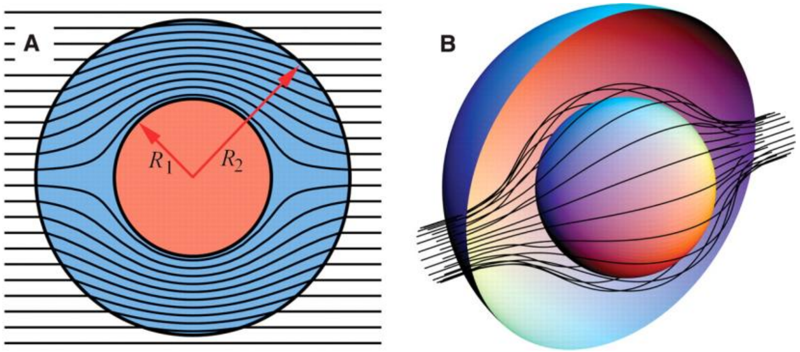




R. A. Shelby, D. R. Smith, S. Schultz, *Science* **84**, 4184 (2001)

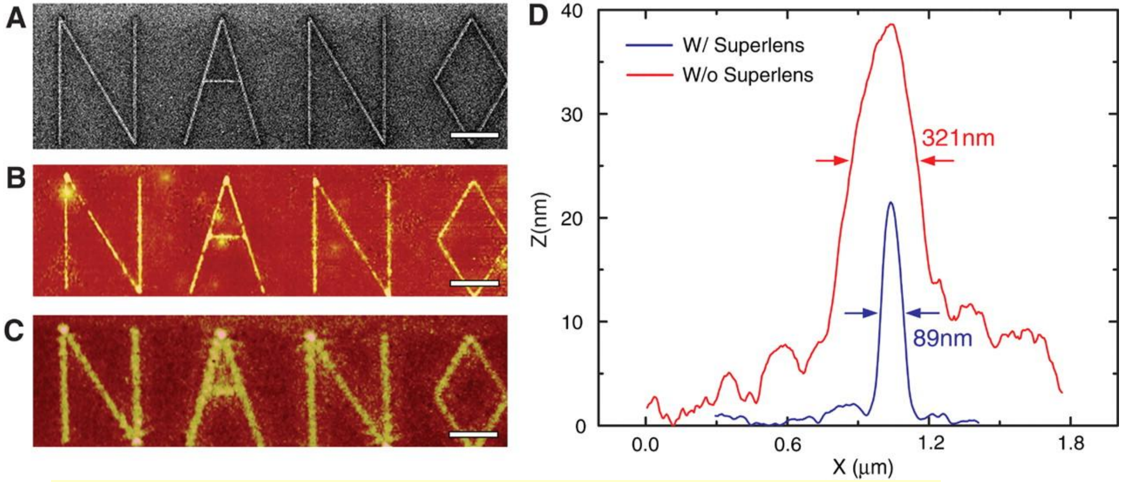
Emergent Phenomena in Metamaterials

- ☐ Cloaking and transformation optics



J. B. Pendry *et al.*, *Science* **312**, 1780-1782 (2006).

- ☐ Superlens – breaking the diffraction limits



N. Fang *et al.*, *Science* **308**, 534-537 (2005).

Bulk Metamaterials vs. Planar Meta-Surfaces

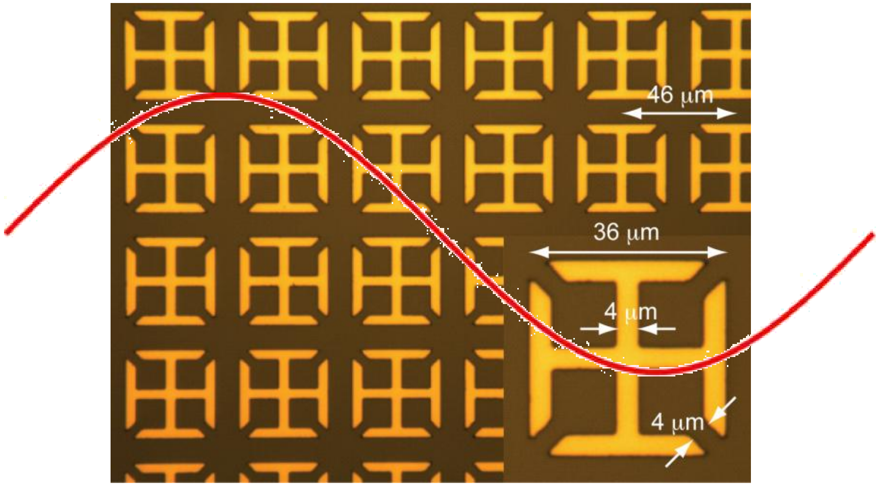
Bulk metamaterials

- Effective material parameters: ε, μ, n, Z
- Difficult to fabricate in the optical regime
- High loss due to the resonant response

Meta-surfaces

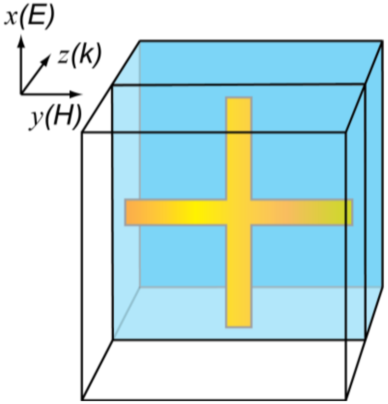
- Effective surface properties
- Planar structures: easy to fabrication for any frequencies
- Reasonably low loss

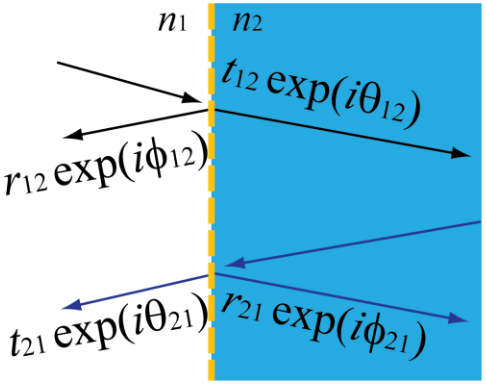
D. Schurig *et al.*, *Science* **314**, 977 (2006).



H. T. Chen *et al.*, *Opt. Express* **15**, 1084 (2007).

Tailored Transmission and Reflection in Meta-Surfaces




n1
n2
$t_{12}\exp(i\theta_{12})$
$r_{12}\exp(i\phi_{12})$
$t_{21}\exp(i\theta_{21})$
$r_{21}\exp(i\phi_{21})$

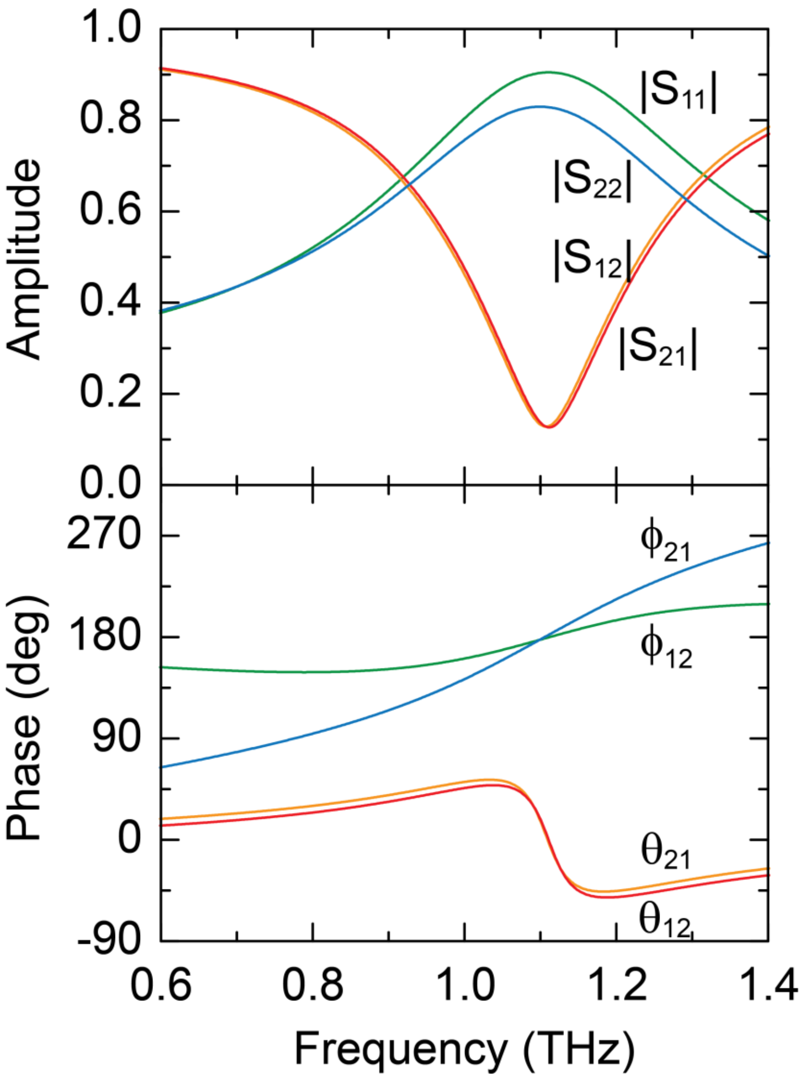
- ☐ The resonator array modifies the complex reflection and transmission coefficients at the interface

$$r_{12} = |S_{11}| \quad t_{12} = \sqrt{\frac{n_1}{n_2}}\,|S_{21}|$$

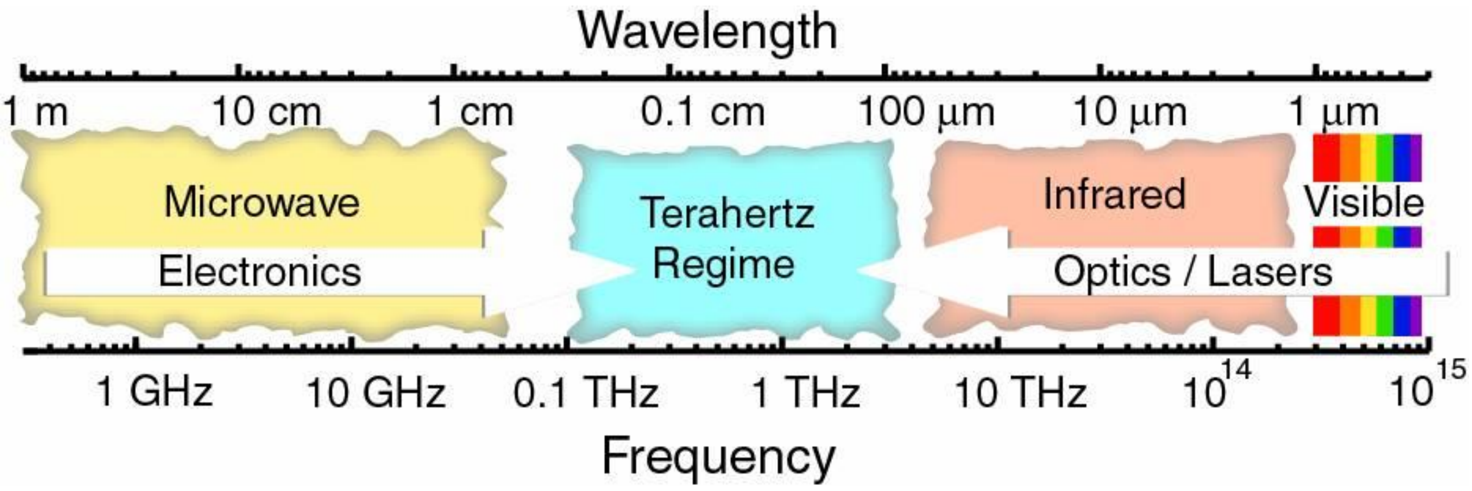
$$r_{21} = |S_{22}| \quad t_{21} = \sqrt{\frac{n_2}{n_1}}\,|S_{21}|$$

$$\phi_{12} = \arctan(S_{11}) \quad \theta_{12} = \arctan(S_{21})$$

$$\phi_{21} = \arctan(S_{22}) \quad \theta_{12} = \arctan(S_{12})$$



Challenges in THz Science and Technology


Wavelength
1 m
10 cm
1 cm
0.1 cm
100 µm
10 µm
1 µm
Microwave
Electronics
Terahertz
Regime
Infrared
Visible
Optics / Lasers
1 GHz
10 GHz
0.1 THz
1 THz
10 THz
10^14
10^15
Frequency

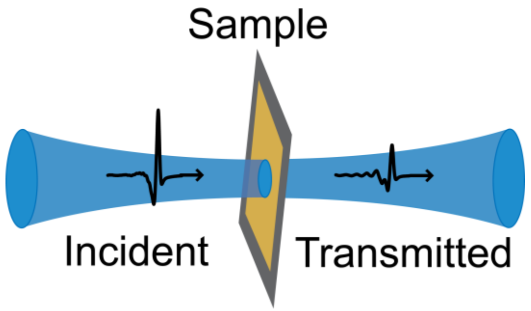
☐ THz is one of the least developed and most challenging regimes in the electromagnetic spectrum

☐ Classical electronics and quantum photonics in general cannot be directly translated to the THz regime

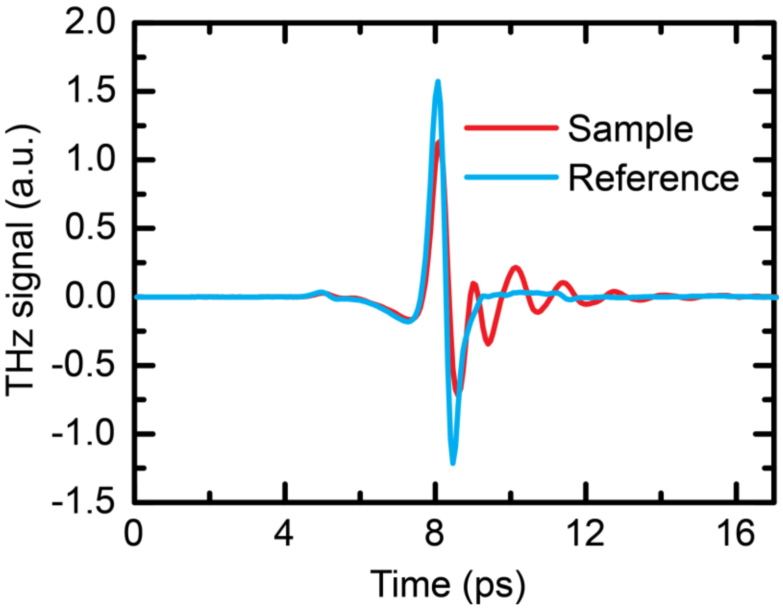
☐ THz sources and detectors are limited

☐ Functional THz devices and components are not widely available

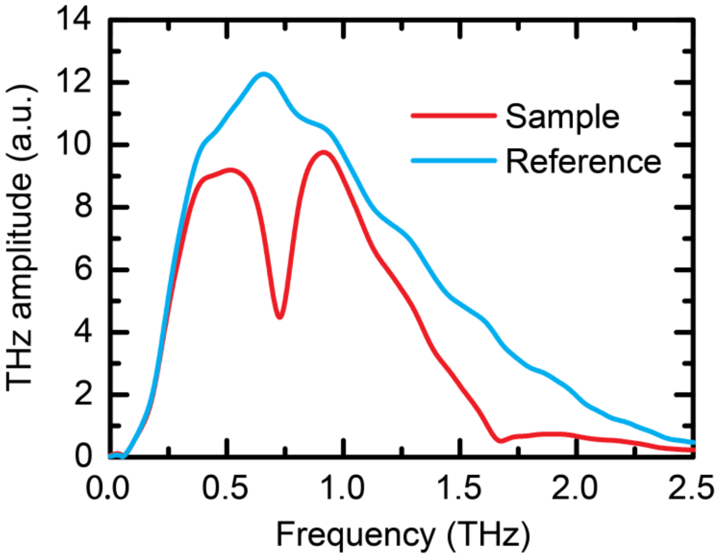
Terahertz Time-Domain Spectroscopy

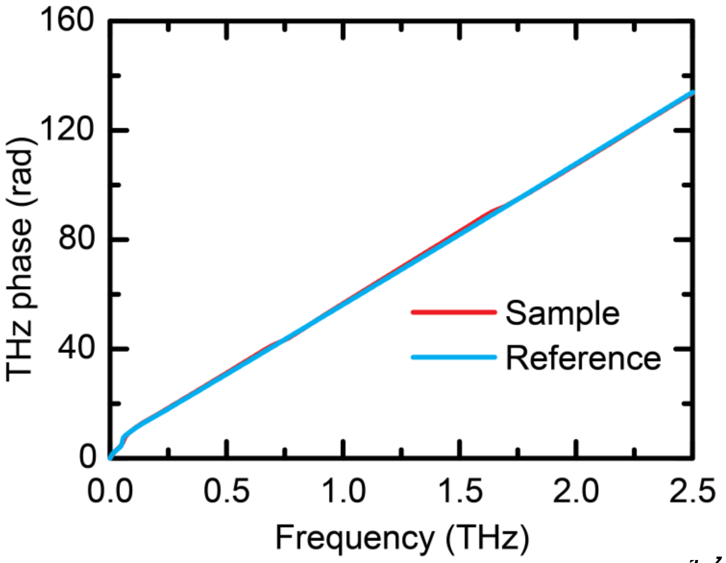


Sample
Incident
Transmitted



FFT

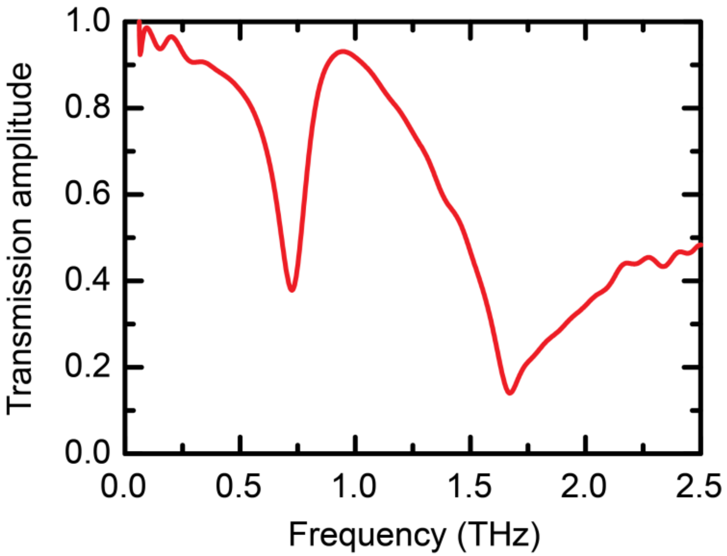


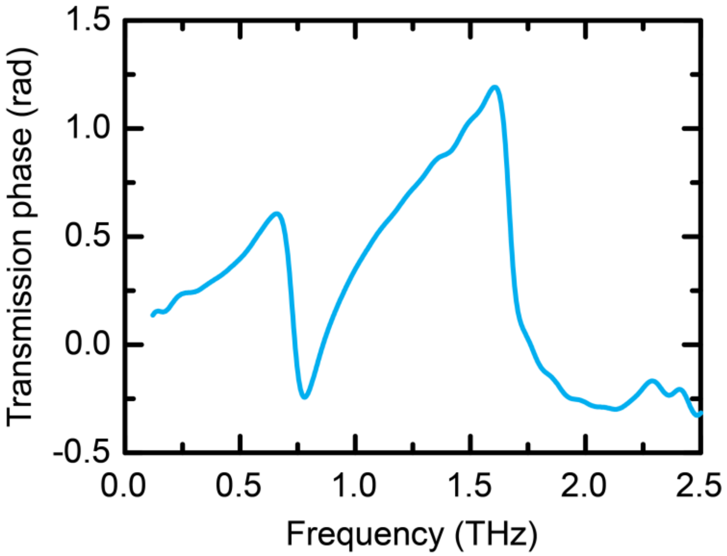


Terahertz Time-Domain Spectroscopy

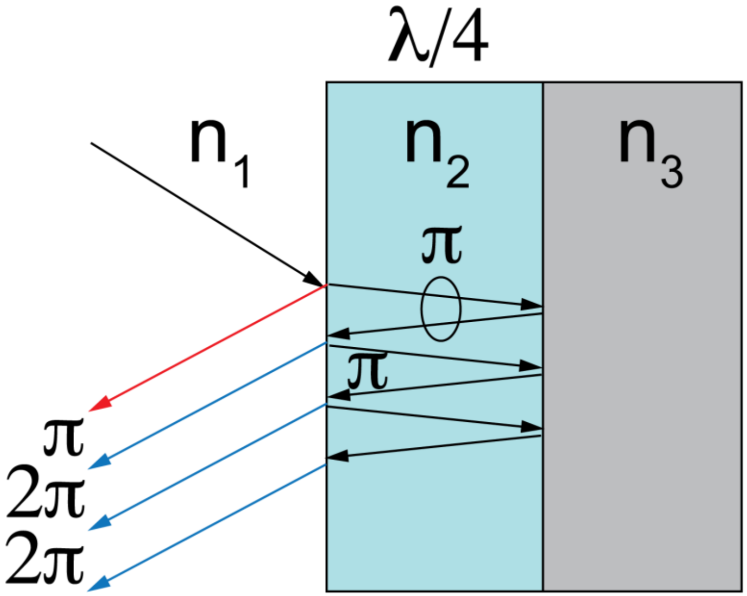
$$\tilde{t}(\omega) = \frac{E_{\mathbf{Sam}}(\omega)}{E_{\mathbf{Ref}}(\omega)}$$

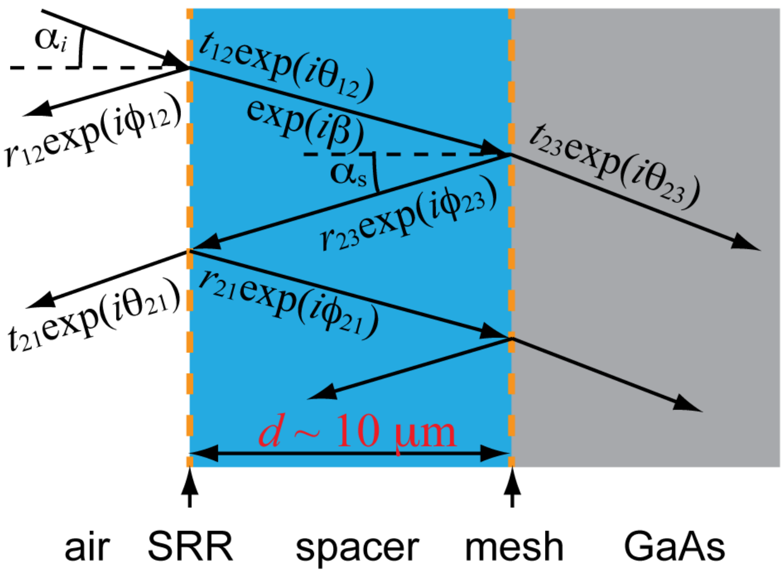
- ☐ Obtain simultaneously the amplitude and phase information
- ☐ To extract complex dielectric function $\varepsilon(\omega)$ over a broad frequency range (non-magnetic materials)
- ☐ Reflection measurement is also required to further extract the complex permeability $\mu(\omega)$ for materials with magnetic response





Antireflection Coatings


λ/4
n_1
n_2
n_3
π
π
π
2π
2π


α_i
$t_{12}\exp(i\theta_{12})$
$r_{12}\exp(i\phi_{12})$
$\exp(i\beta)$
α_s
$t_{23}\exp(i\theta_{23})$
$r_{23}\exp(i\phi_{23})$
$t_{21}\exp(i\theta_{21})$
$r_{21}\exp(i\phi_{21})$
$d \sim 10\ \mu\text{m}$
air
SRR
spacer
mesh
GaAs

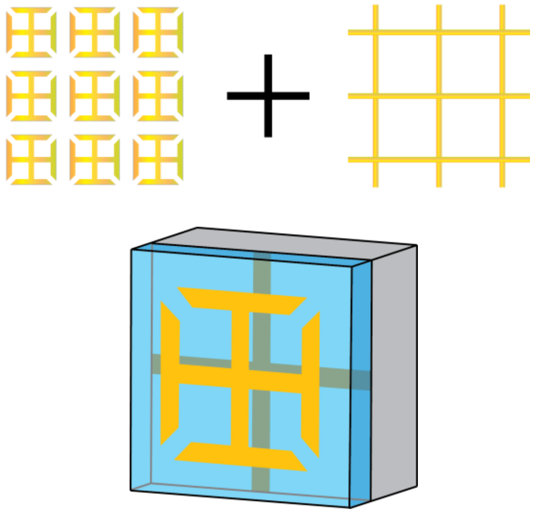
- ☐ $n_2 = (n_1 n_3)^{1/2} \rightarrow r_{12} = r_{21} = r_{23}$
- ☐ Phase difference π between direct reflection and second reflection
- ☐ Phase difference 2π in the following reflections

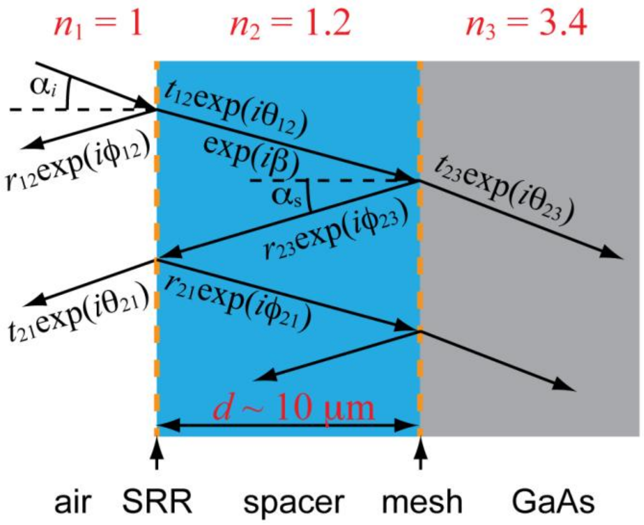
$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

$$\tilde{t} = \frac{\tilde{t}_{12}\tilde{t}_{23}e^{i\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

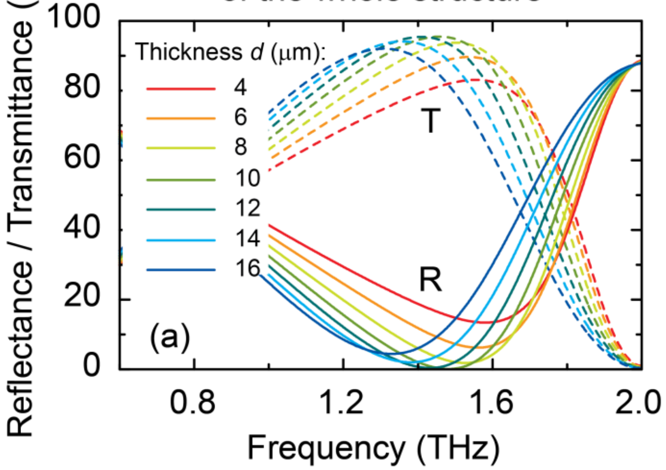
Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Ultrathin Metamaterial Anti-Reflection Coating

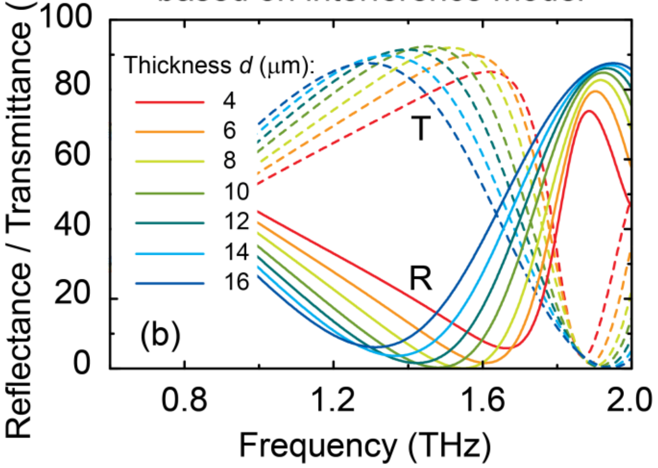



$n_1 = 1$
$n_2 = 1.2$
$n_3 = 3.4$
α_i
$r_{12}\exp(i\phi_{12})$
$t_{12}\exp(i\theta_{12})$
$\exp(i\beta)$
α_s
$t_{23}\exp(i\theta_{23})$
$r_{23}\exp(i\phi_{23})$
$t_{21}\exp(i\theta_{21})$
$r_{21}\exp(i\phi_{21})$
$d \sim 10\ \mu\text{m}$
air
SRR
spacer
mesh
GaAs

Numerical similation of the whole structure

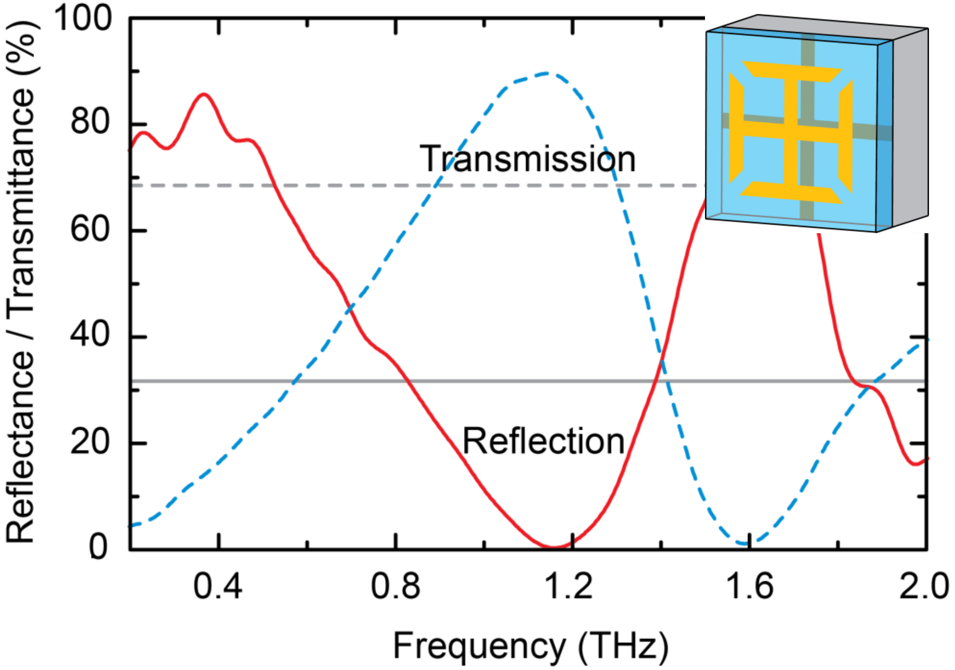


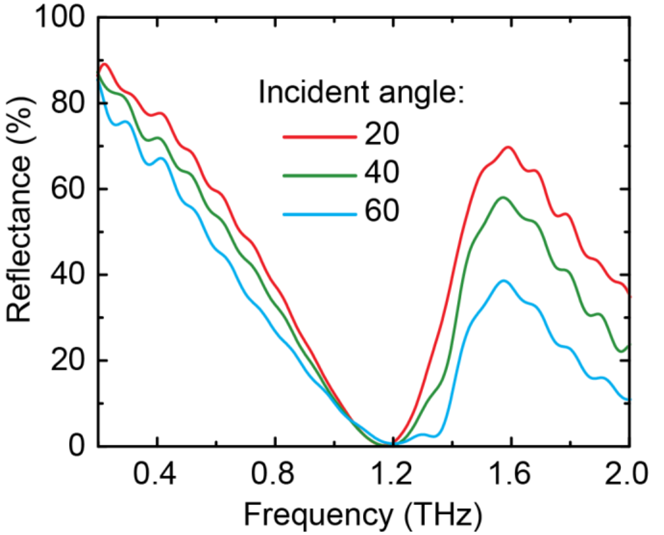
Quasi-analytical calculation based on interference model



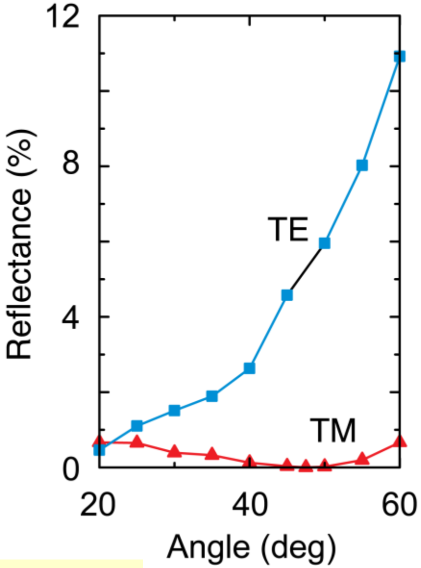
Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Ultrathin Metamaterial ARC: Experiments



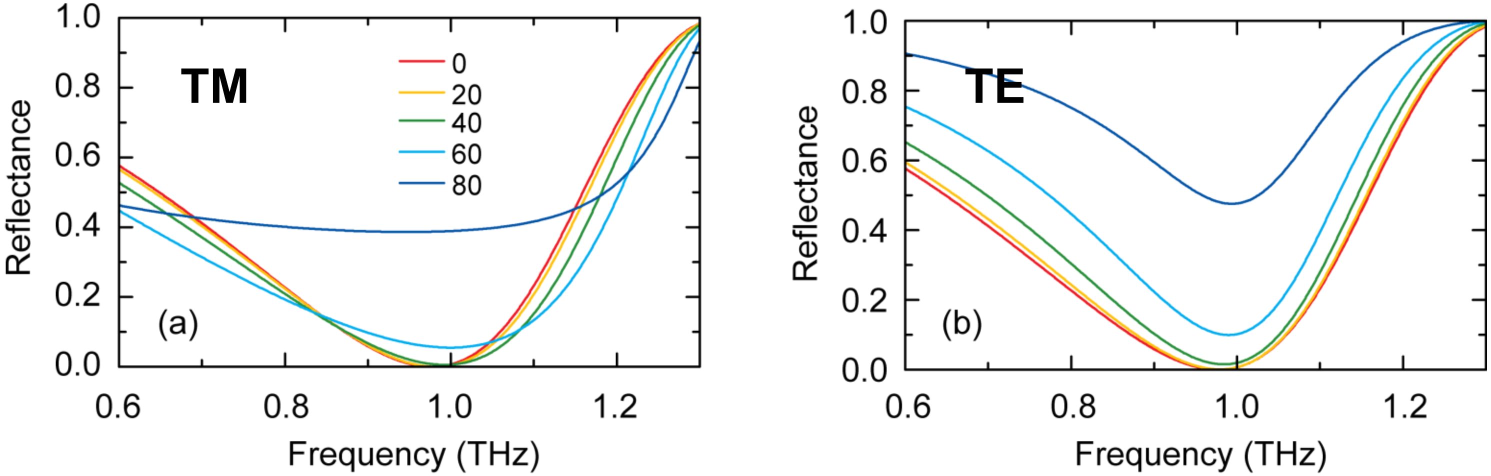


- Reflectance: 32% → ~0
- Transmittance: 68% → 90%
- Transmittance does not reach 100% due to losses
- Operate over a wide incident angle range
- Brewster angle behavior for TM polarization

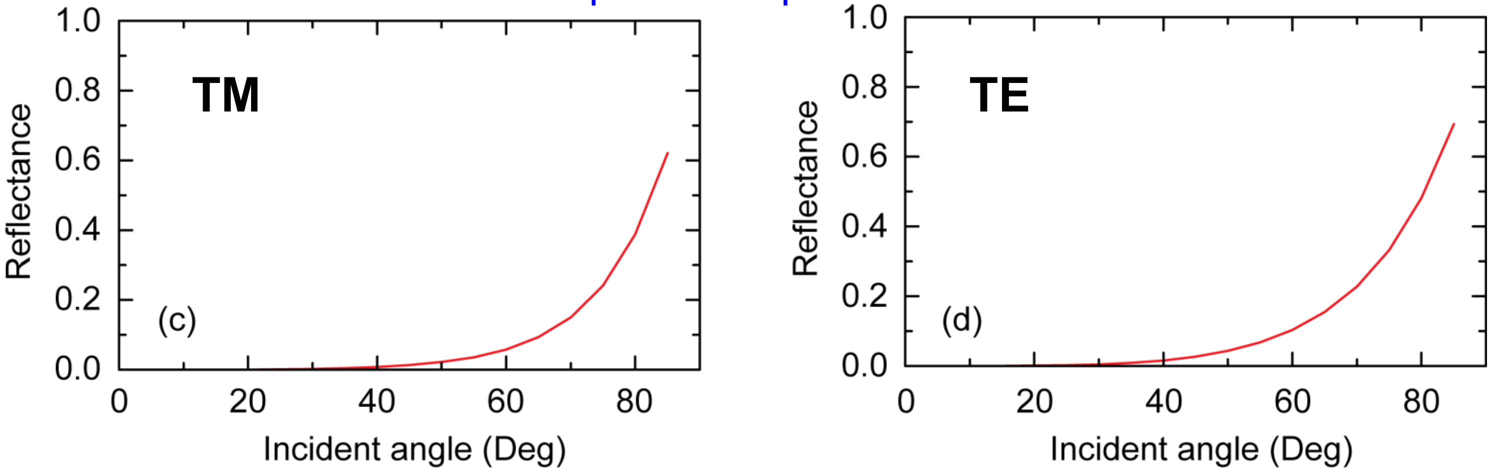


Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Incident Angular Dependence: Numerical Simulations



With optimized spacer thickness



Chen *et al.*, *THz Sci. & Technol.* **3**, 66 (2010).

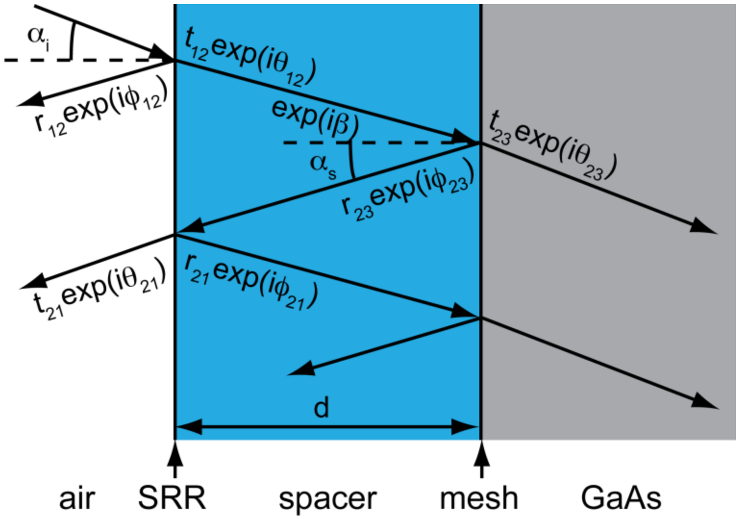
Antireflection Mechanism: Modeling Results

- Antireflection requirements:

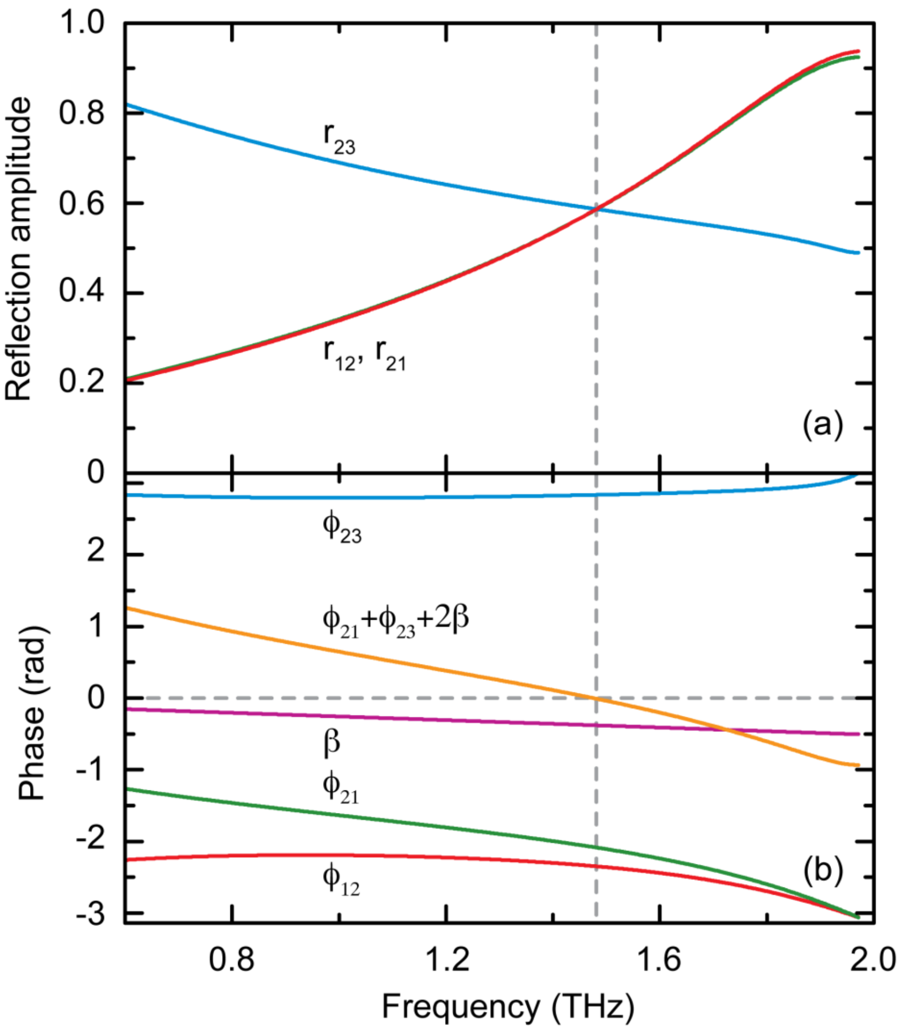
$$r_{12} = r_{21} = r_{23},$$

$$\phi_{21} + \phi_{23} + 2\beta = 2m\pi$$

- Varying β (spacer thickness) reproduces the thickness dependent reflection and transmission



α_i
$t_{12}\exp(i\theta_{12})$
$r_{12}\exp(i\phi_{12})$
$\exp(i\beta)$
α_s
$t_{23}\exp(i\theta_{23})$
$r_{23}\exp(i\phi_{23})$
$t_{21}\exp(i\theta_{21})$
$r_{21}\exp(i\phi_{21})$
d
air
SRR
spacer
mesh
GaAs



Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

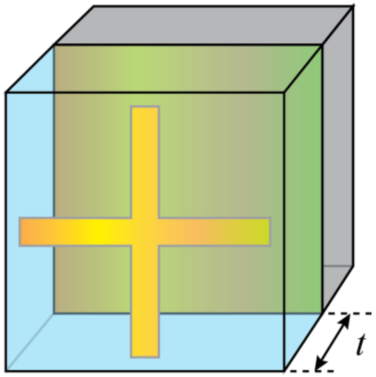
Advantages of Metamaterial Antireflection

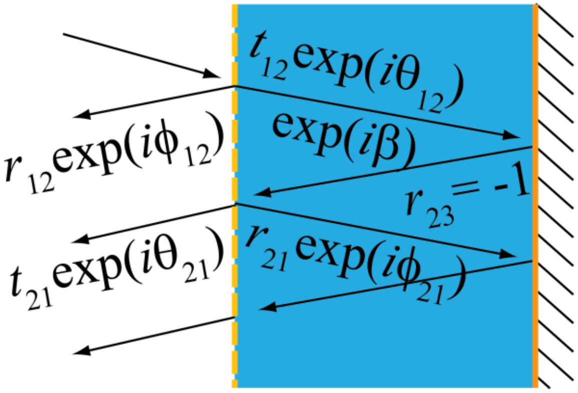
- ☐ The overall thickness is much smaller than the wavelength (~λ/20)

- ☐ With any dielectric constant of the spacer material, there is always a thickness achieving excellent antireflection, even the spacer dielectric constant is larger than the substrate

- ☐ The losses in metal and the spacer material mainly affect the transmittance, but has little effect on the reflectance

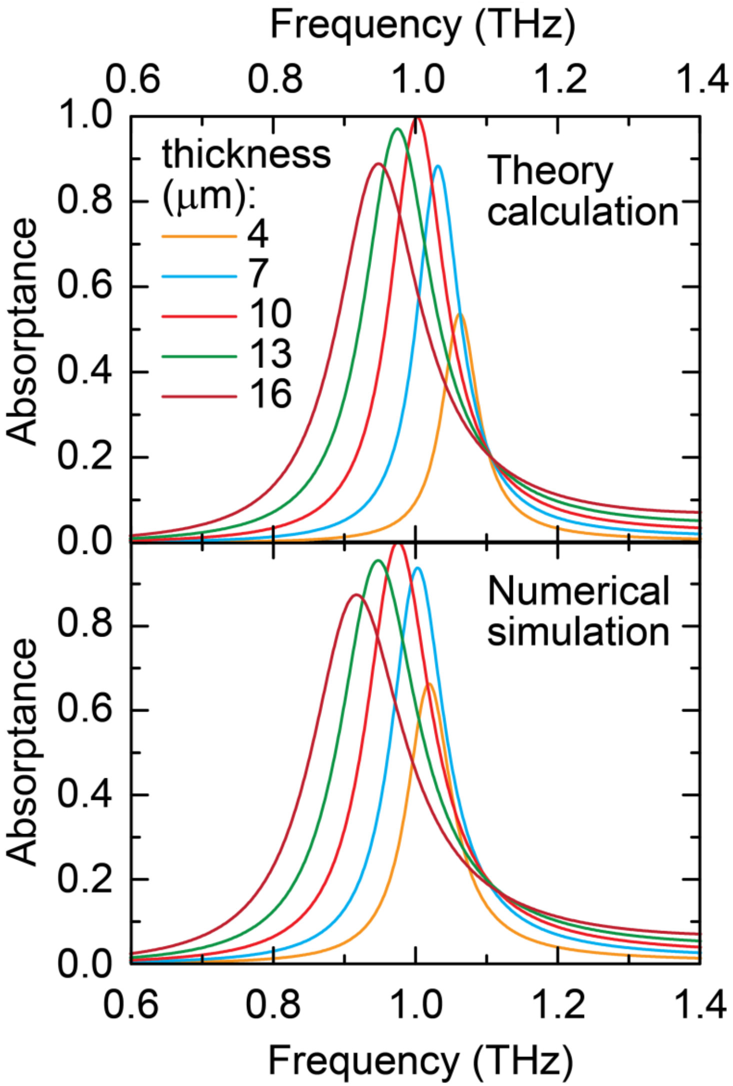
Metamaterial Perfect Absorbers: Trapped Light




$t_{12}\exp(i\theta_{12})$
$\exp(i\beta)$
$r_{12}\exp(i\phi_{12})$
$r_{23} = -1$
$t_{21}\exp(i\theta_{21})$
$r_{21}\exp(i\phi_{21})$

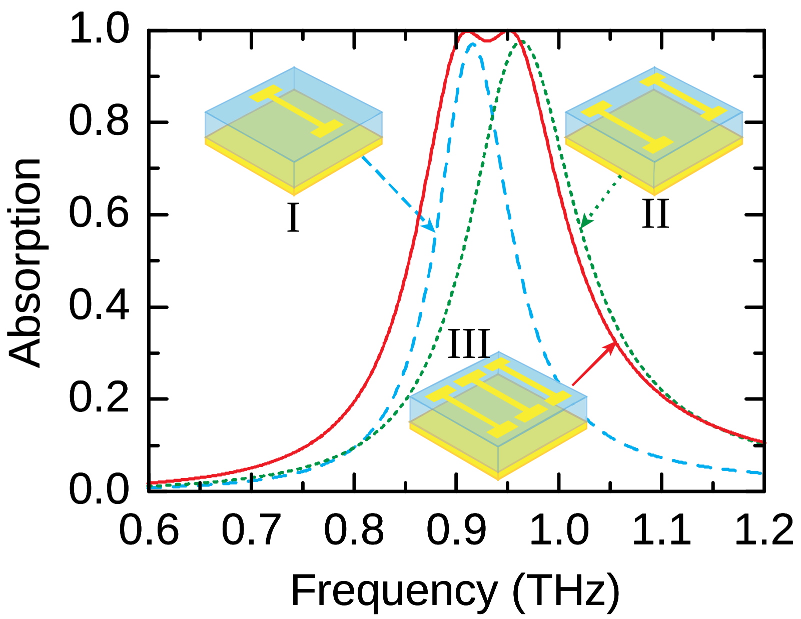
$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

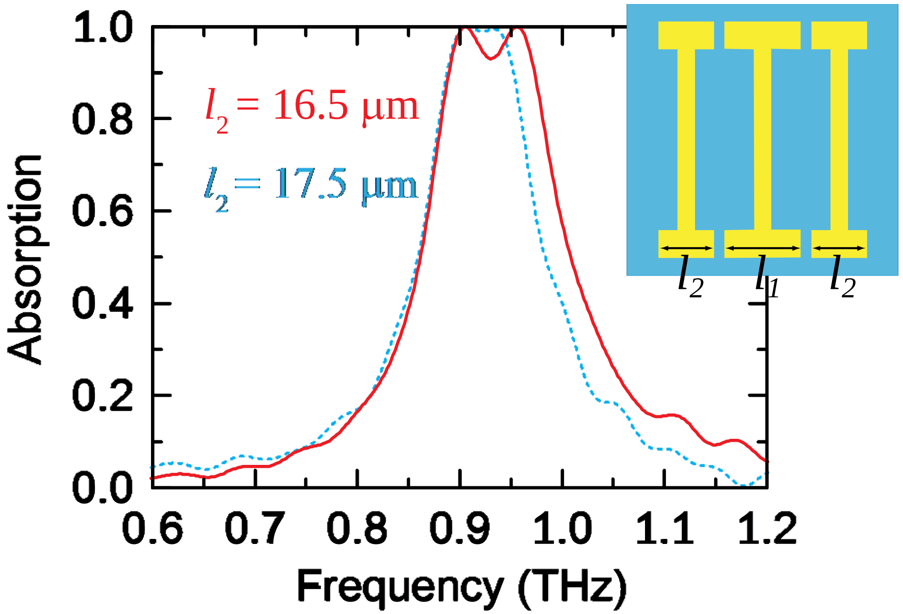
- Zero transmission due to the metal ground plane
- Minimizing reflection due to destructive interference of multi-reflection
- Absorptance: *A* = *1 – R*



Chen, *Opt. Express* **20,** 7165 (2012).

Broaden the Bandwidth of Metamaterial Perfect Absorbers

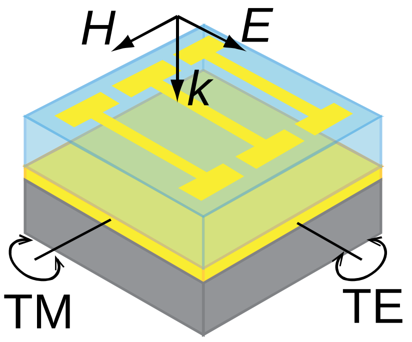

Simulations

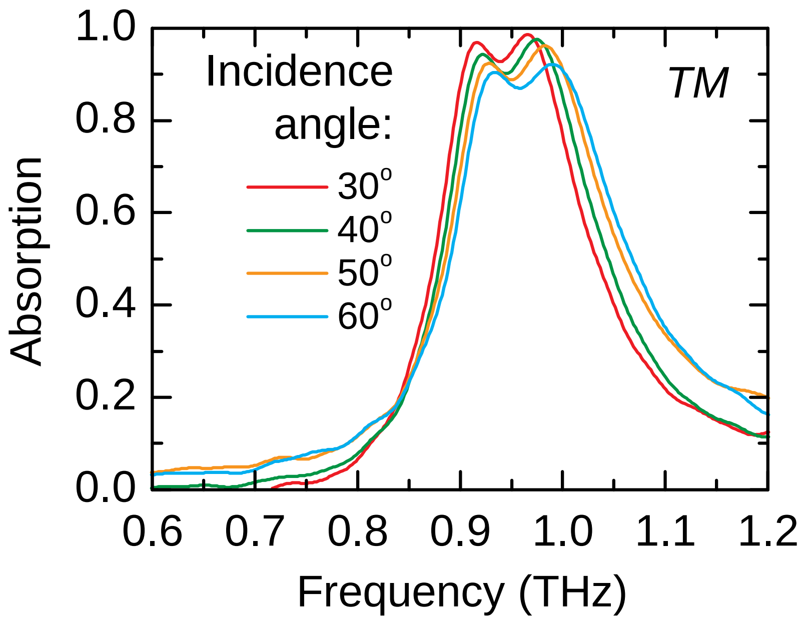

Experiments

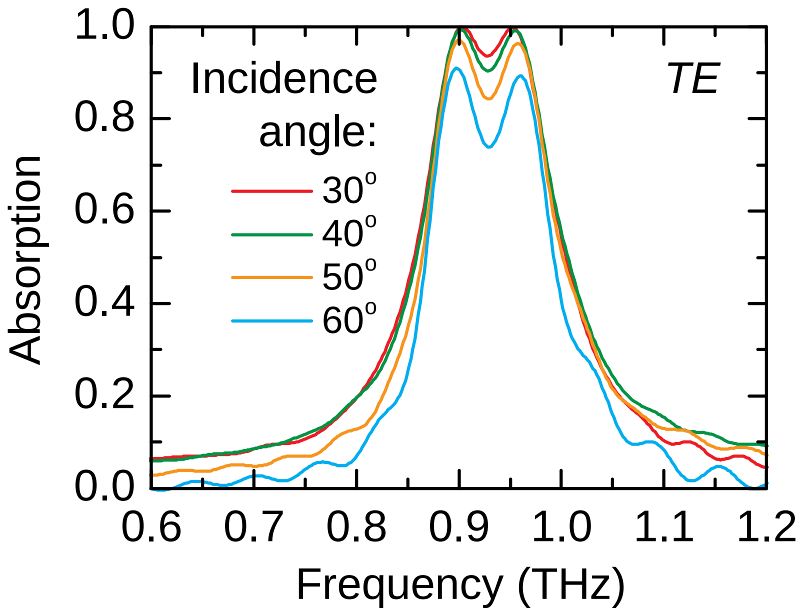
- ☐ Broadening the absorption bandwidth by multiplexing

Huang *et al.*, *Opt. Lett.* **37,** 154 (2012).

High Absorption over a Wide Incident Angle Range







Huang *et al.*, *Opt. Lett.* **37,** 154 (2012).

Boundary Surface Currents

- ☐ When EM wave first incident to the resonator array interface, the boundary conditions for magnetic field give the surface current:

$$J_c = \left[\left(1 - \tilde{r}_{12}\right)/Z_0 - \tilde{t}_{12}/Z_s \right] E_c^i$$

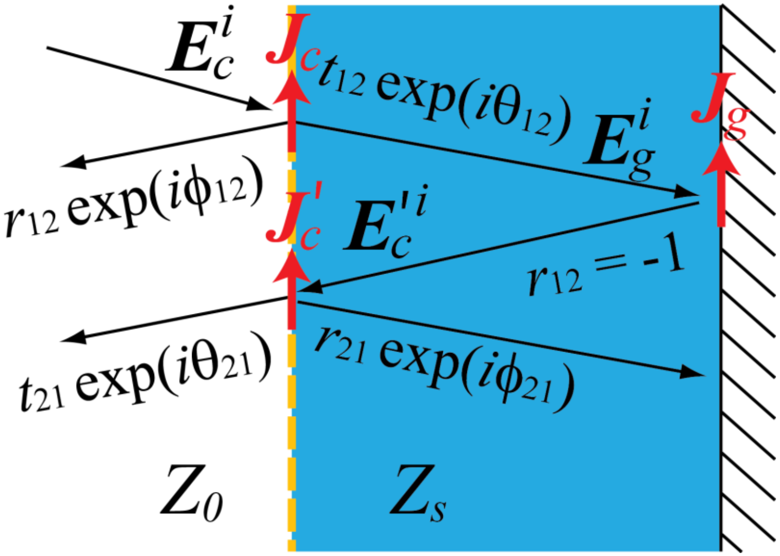
- ☐ Then it reaches to ground plane and is reflected, the boundary conditions for magnetic field require:

$$J_g = 2E_g^i/Z_s = 2\tilde{t}_{12}e^{i\tilde{\beta}}E_c^i/Z_s$$

- ☐ It reaches to resonator interface again:

$$J_c' = \left[\left(1 - \tilde{r}_{21}\right)/Z_s - \tilde{t}_{21}/Z_0 \right] E_c'^i$$

$$= -\left[\left(1 - \tilde{r}_{21}\right)/Z_s - \tilde{t}_{21}/Z_0 \right] \tilde{t}_{12}e^{i2\tilde{\beta}}E_c^i$$


E_c^i
J_c
$t_{12}\exp(i\theta_{12})$
E_g^i
J_g
$r_{12}\exp(i\phi_{12})$
J_c'
$E_c'^i$
r_{12} = -1
$t_{21}\exp(i\theta_{21})$
$r_{21}\exp(i\phi_{21})$
Z_0
Z_s

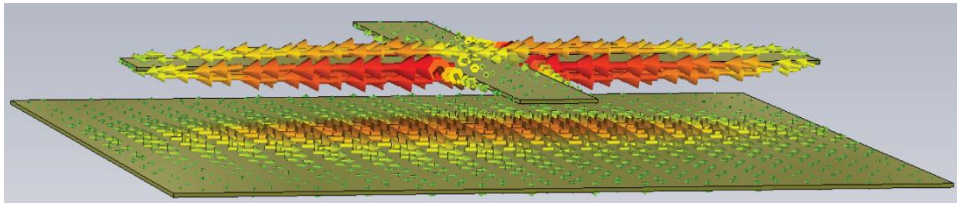
Chen, *Opt. Express* **20,** 7165 (2012).

Anti-Parallel Surface Currents by Electrical Excitations

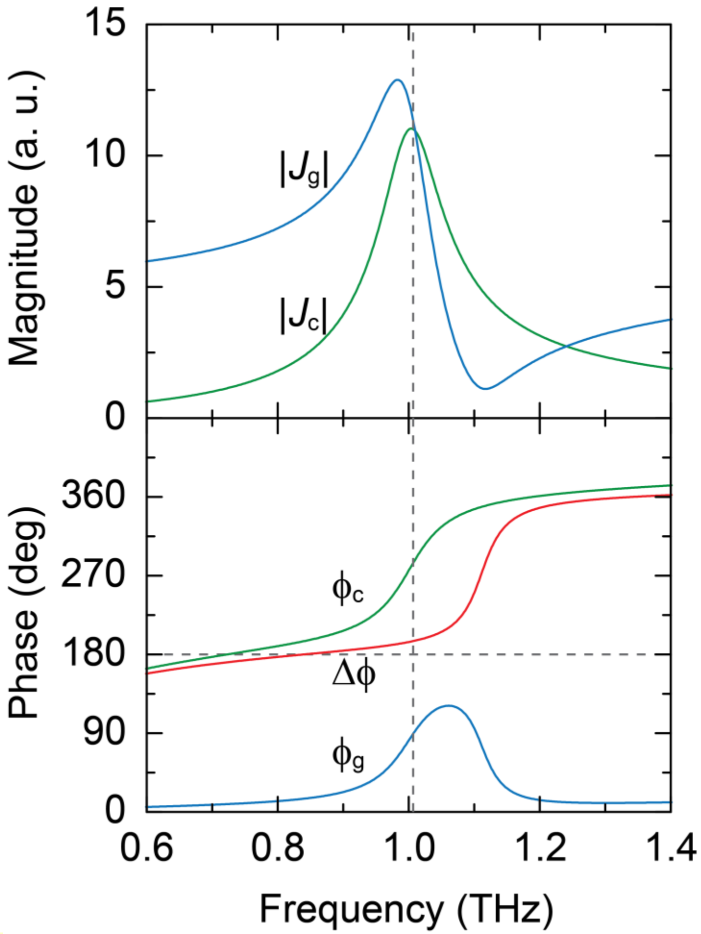
$$J_c^{total} \propto -\frac{\left[\left(1-\tilde{r}_{21}\right)/Z_s-\tilde{t}_{21}/Z_0\right]\tilde{t}_{12}e^{i2\tilde{\beta}}}{1+\tilde{r}_{21}e^{i2\tilde{\beta}}}+\left[\left(1-\tilde{r}_{12}\right)/Z_0-\tilde{t}_{12}/Z_s\right]$$

$$J_g^{total} \propto \frac{2\tilde{t}_{12}e^{i\tilde{\beta}}}{1+\tilde{r}_{21}e^{i2\tilde{\beta}}}/Z_s$$

- The total surface currents are the superpositions of each excitation:

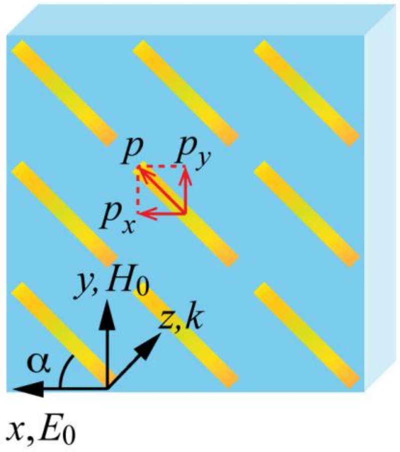


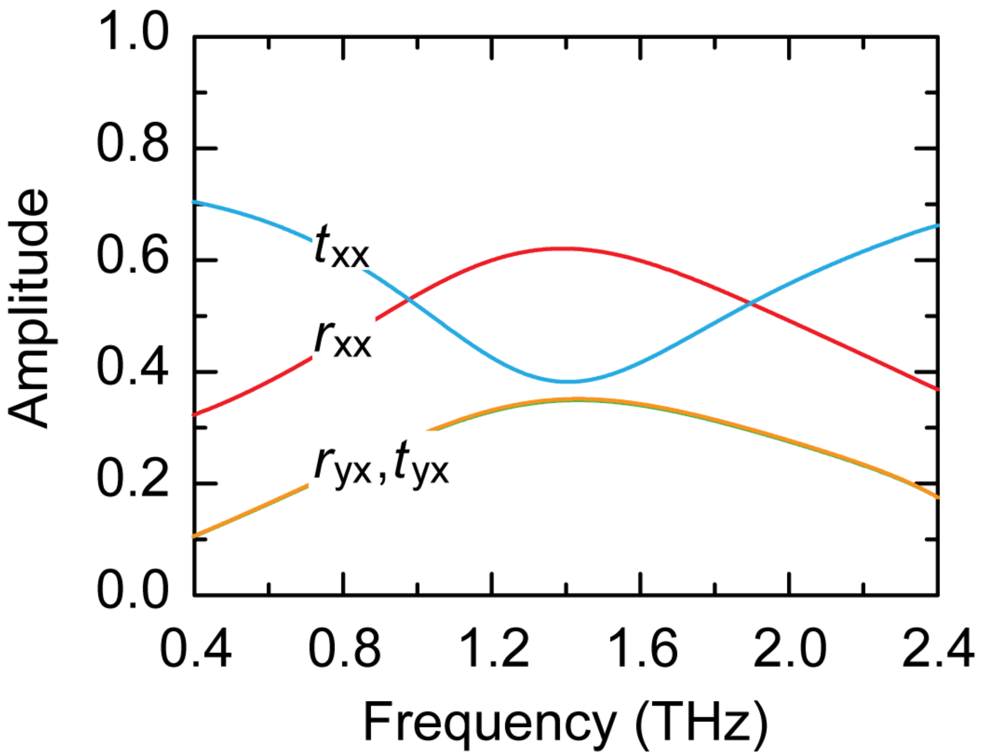
- Anti-parallel surface currents are due to interference and superposition of electrical excitations



Chen, *Opt. Express* **20,** 7165 (2012).

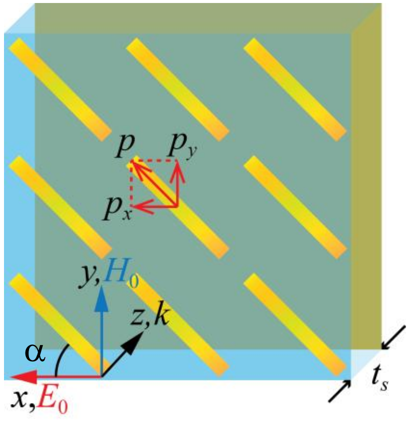
Polarization Conversion in Anisotropic MMs





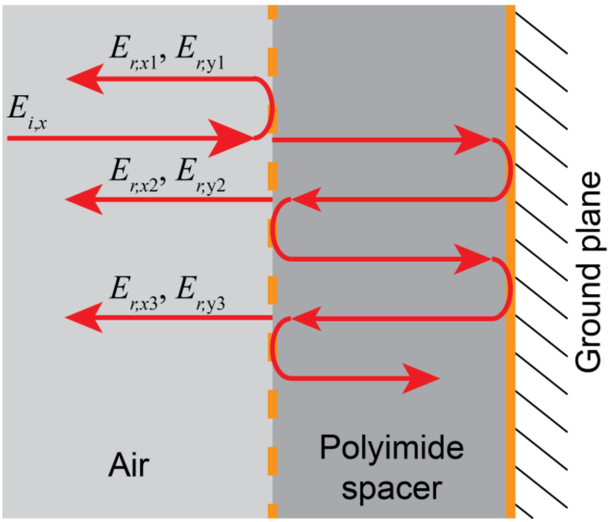
- Incident field $\boldsymbol{E}_0$ along x-direction (α=45°): the excited dipole $\boldsymbol{p}$ has x- and y-components
- p_x: co-polarized reflection and transmission
- p_y: cross-polarized reflection and transmission
- Single-layered metamaterial: polarization conversion is low
- Output waves are elliptically polarized

Metamaterial Polarization Converter: Reflection

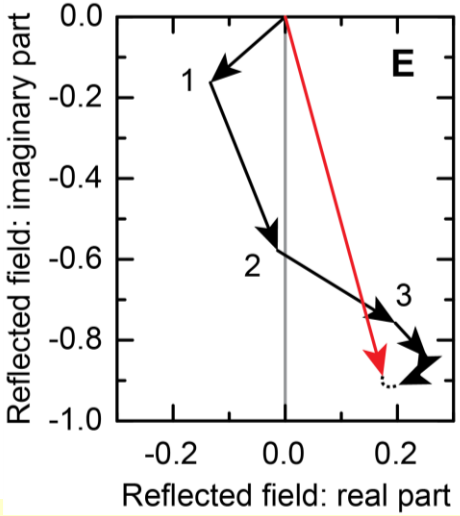

p
p_y
p_x
y, H_0
z, k
α
x, E_0
t_s

- Backed with a metal ground plane with appropriate thick dielectric spacer
- Multiple reflections contain both x and y components
- The co-polarized multiple reflections interfere destructively, leading to minimal co-polarized reflection
- The cross-polarized multiple reflections interfere constructively, leading to high cross-polarized reflection

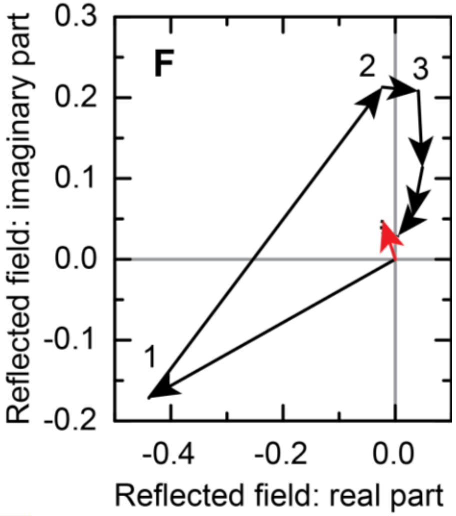
Cut-wire array


$E_{r,x1}, E_{r,y1}$
$E_{i,x}$
$E_{r,x2}, E_{r,y2}$
$E_{r,x3}, E_{r,y3}$
Ground plane
Air
Polyimide spacer

cross-polarized

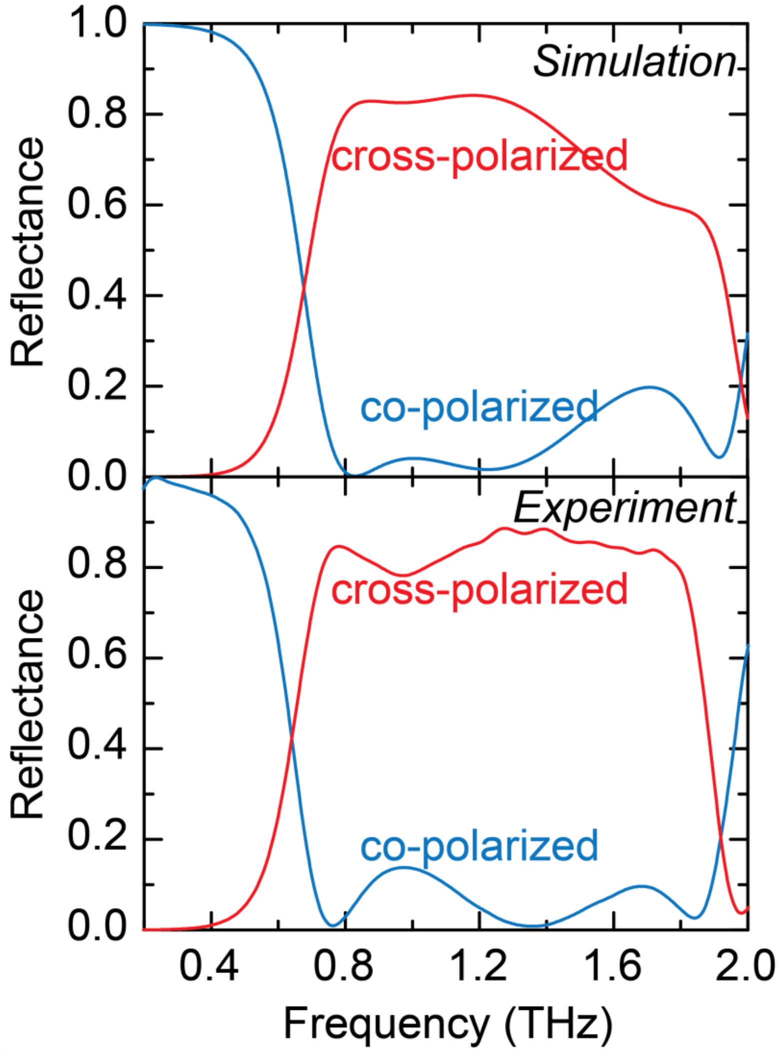


co-polarized



Grady et al., *Science* **340**, 1304 (2013).

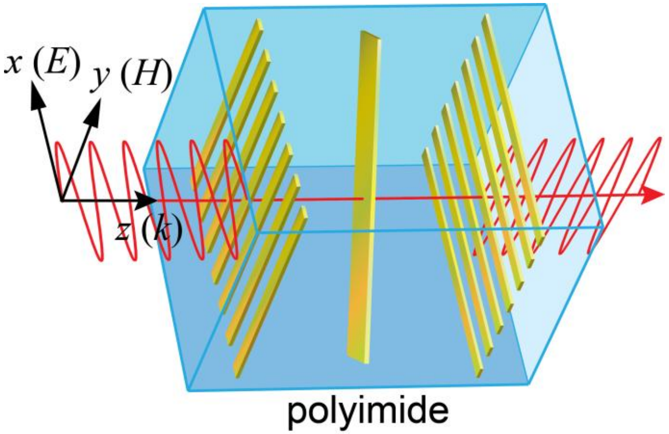
Metamaterial Polarization Converter: Reflection

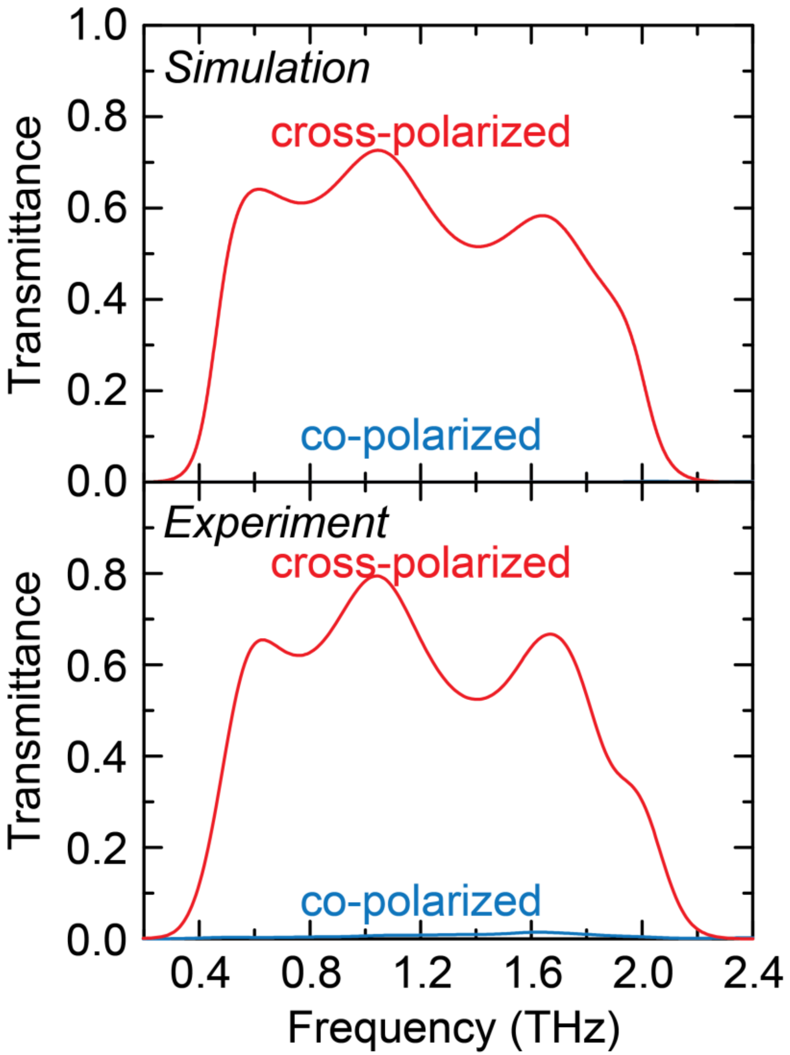


- ☐ Demonstrated in both simulations and experiments
- ☐ Device thickness 33 μm
- ☐ Co-polarized reflection is minimal
- ☐ Cross-polarized reflectance is more than 80%
- ☐ Broadband: destructive interference at multiple frequencies

Grady et al., *Science* **340**, 1304 (2013).

Polarization Converter: Transmission

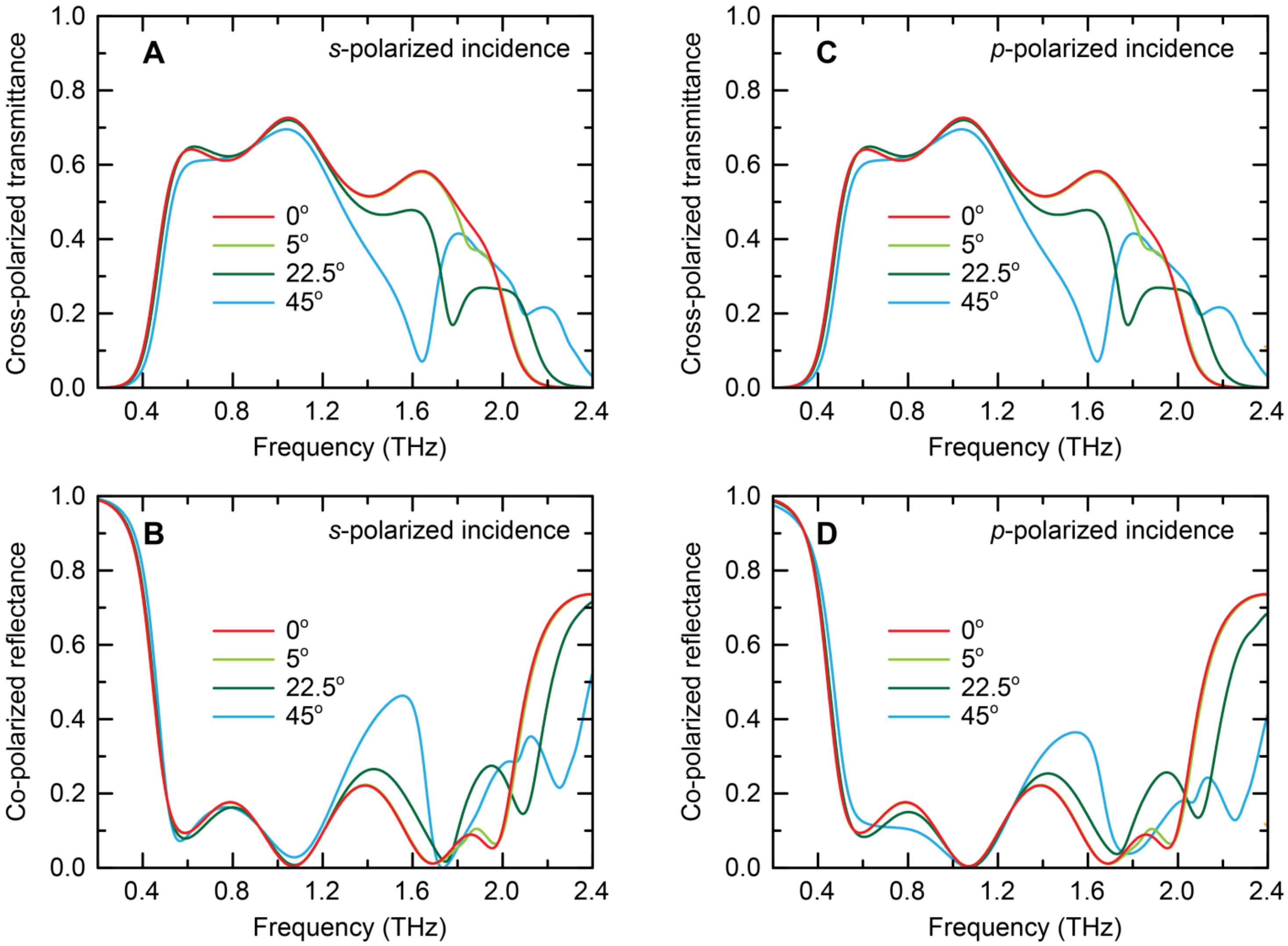




- ☐ The gratings are equivalent to ground plane for electric field polarized along the grating lines.
- ☐ The back grating prevents co-polarized light from transmitting through
- ☐ The front grating prevents the converted cross-polarized light from reflecting back

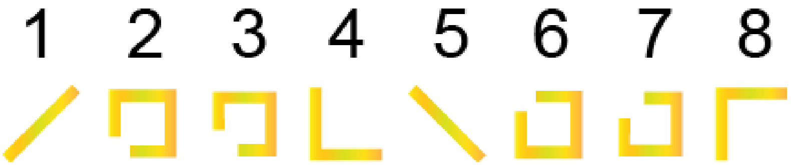
Grady et al., *Science* **340**, 1304 (2013).

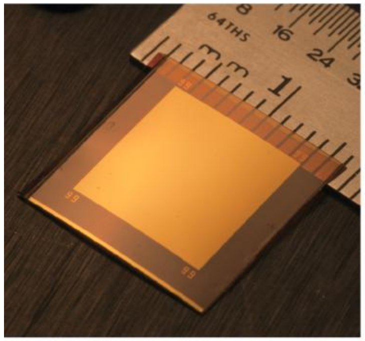
Polarization and Incident Angle Dependence

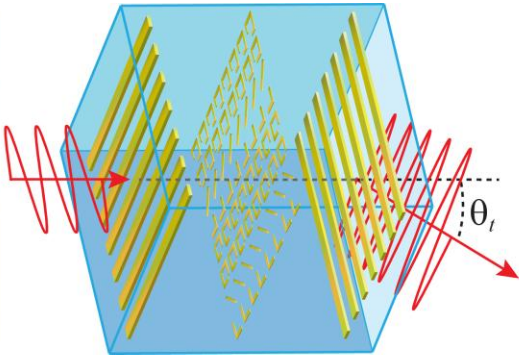


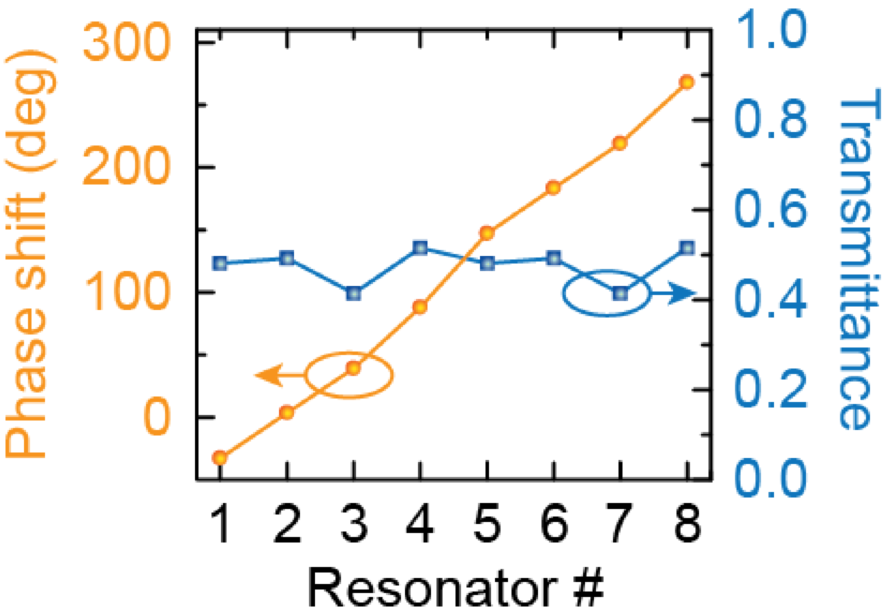
Grady et al., *Science* **340**, 1304 (2013).

Anomalous Refraction: Generalized Snell's Law







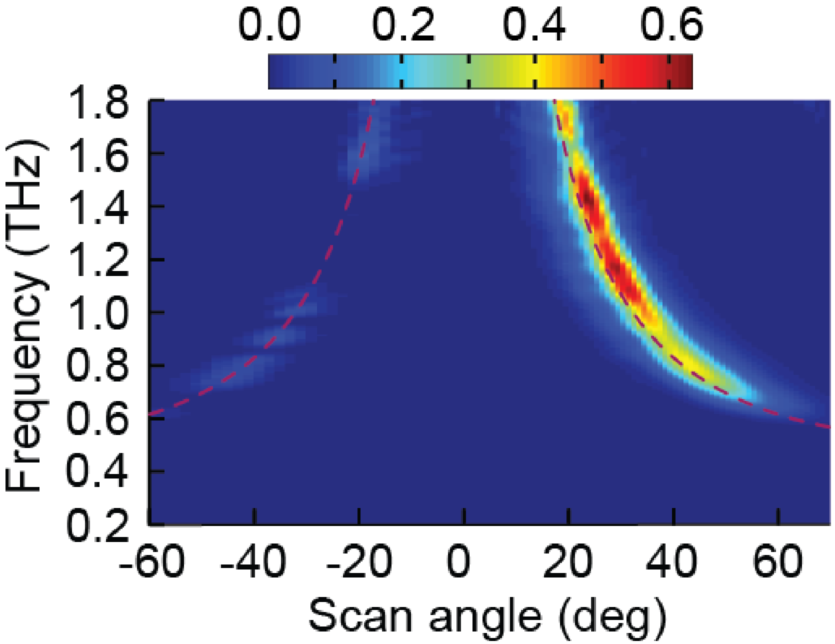


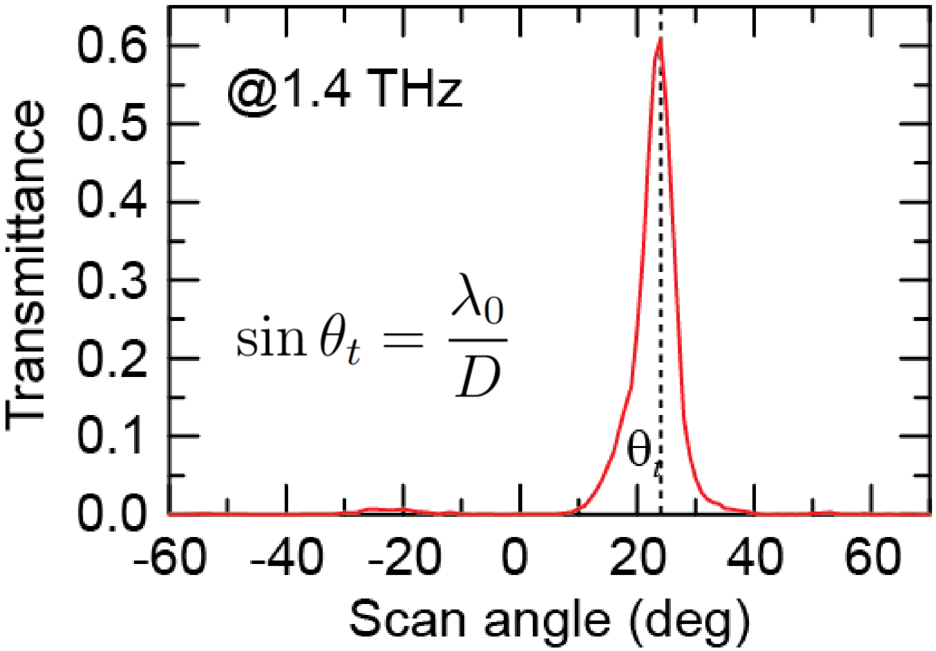
$$\sin\theta_t - \sin\theta_i = \frac{\lambda_0}{2\pi}\frac{\mathrm{d}\Phi}{\mathrm{d}x}$$

- ☐ Each individual element can be used in polarization converter
- ☐ Conversion efficiency is designed to be largely constant
- ☐ 8 elements form the unit cell, with a linear phase shift spanning a 2π range

Grady et al., *Science* **340**, 1304 (2013).

Near-Perfect Anomalous Refraction: Exp.

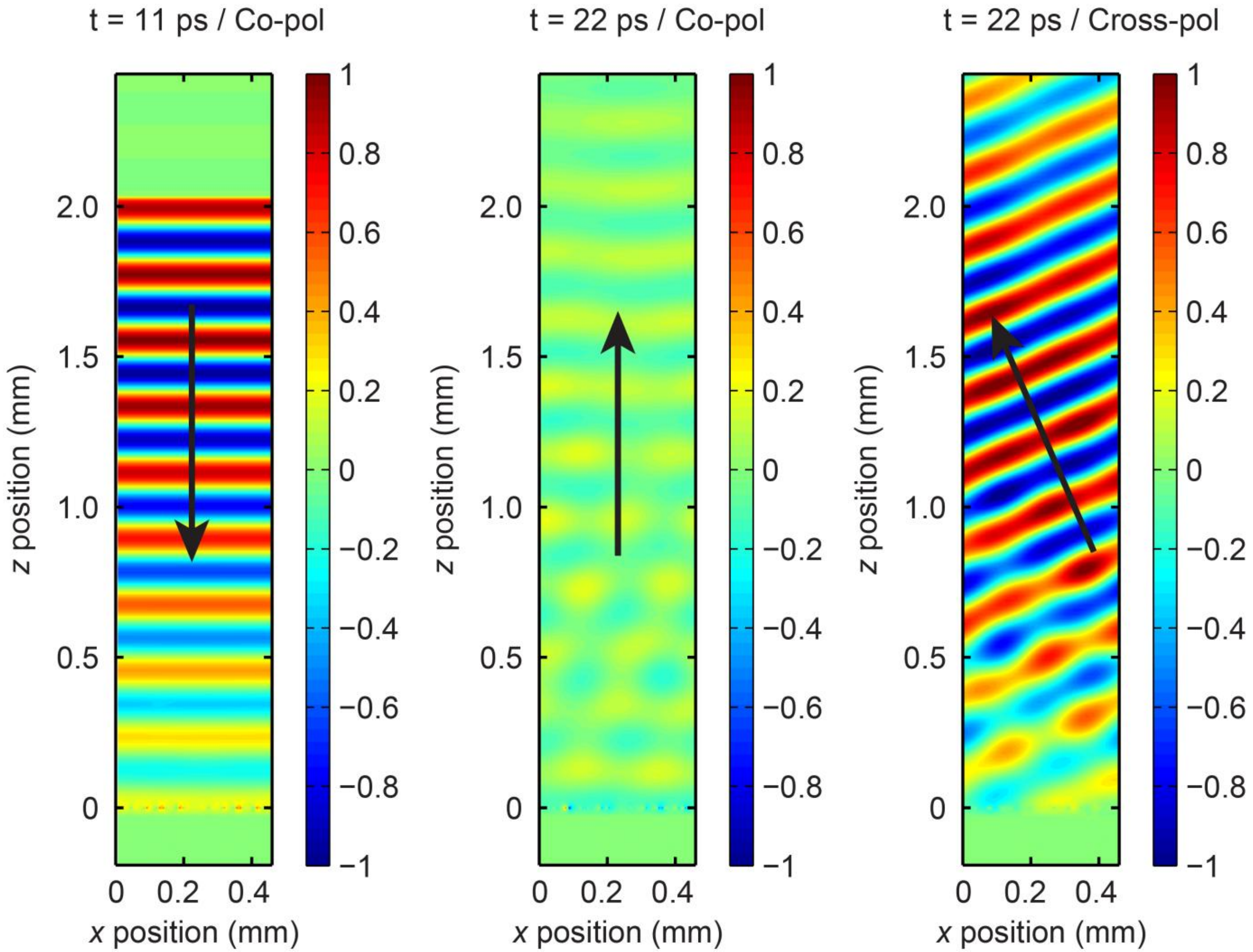




- ☐ At a specific frequency, the “refraction angle” is determined by periodicity
- ☐ At 1.4 THz, the anomalous refraction carries 60% of the incident power
- ☐ Measure the cross-polarized transmission *vs.* scanning angle
- ☐ Operate over a broad bandwidth

Grady et al., *Science* **340**, 1304 (2013).

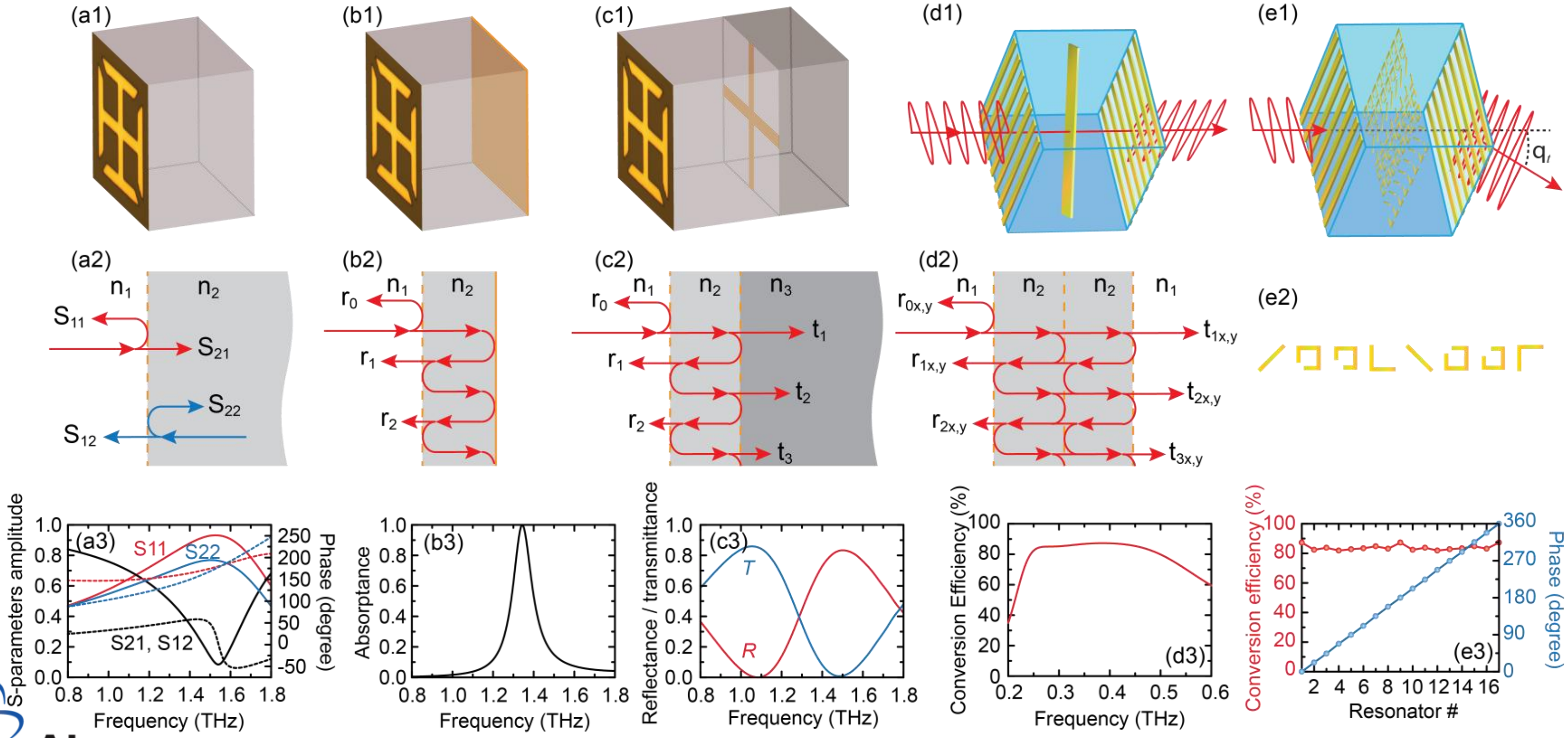
Near-Perfect Anomalous Reflection: Simulation



Grady et al., *Science* **340**, 1304 (2013).

Summary

- ❑ Provide the basic concept of metamaterials and metasurfaces
- ❑ Few-layered ultrathin planar metamaterials can achieve many optical functionalities:



(a1)
(b1)
(c1)
(d1)
(e1)
q_r
(a2)
n1
n2
S11
S21
S22
S12
(b2)
r0
r1
r2
(c2)
n3
t1
t2
t3
(d2)
r0x,y
r1x,y
r2x,y
t1x,y
t2x,y
t3x,y
(e2)
(a3)
S11
S22
S21, S12
S-parameters amplitude
Phase (degree)
1.0
0.8
0.6
0.4
0.2
0.0
250
200
150
100
50
0
-50
0.8
1.0
1.2
1.4
1.6
1.8
Frequency (THz)
(b3)
Absorptance
(c3)
T
R
Reflectance / transmittance
(d3)
Conversion Efficiency (%)
100
80
60
40
20
0
0.2
0.3
0.4
0.5
0.6
(e3)
Conversion efficiency (%)
Phase (degree)
360
270
180
90
0
2
4
6
8
10
12
14
16
Resonator #

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